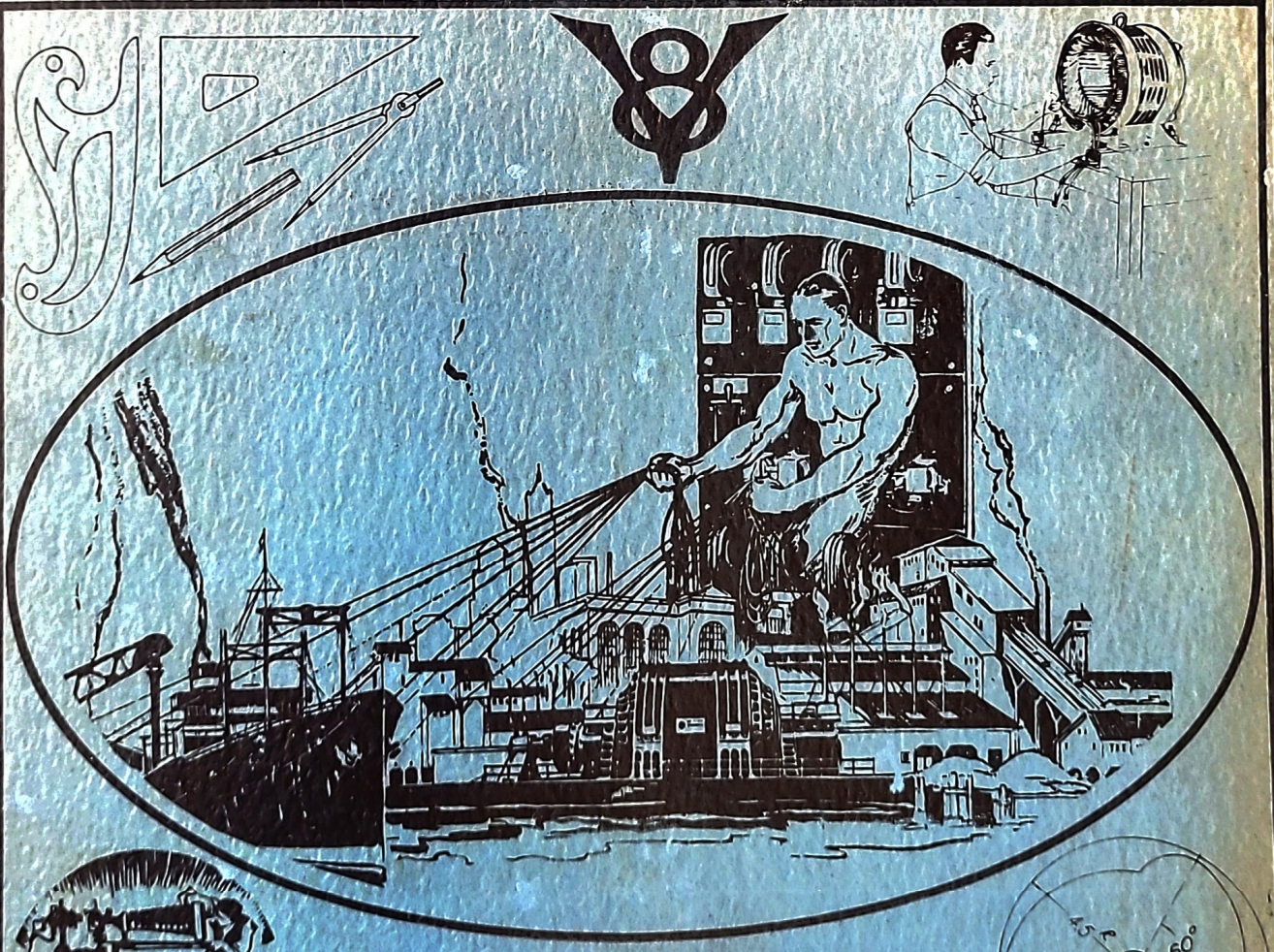
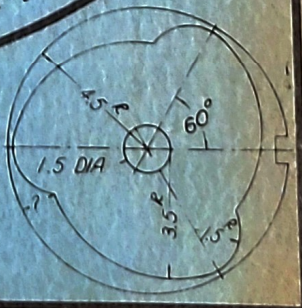
FORD APPRENTICE SCHOOL

VOLUME I

DC

ELECTRICITY





FORD MOTOR CO
DEARBORN MICH

This is one of a series of lesson sheets prepared by instructors in Ford Schools for use in their classes.

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Henry Ford Trade School was founded in 1916 to train mechanics and make it possible for a young boy to partially support himself while attending school. It is incorporated under Michigan law as a non-profit institution. The school occupies three acres of floor space and has class and shop equipment for 1700 students.

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DEARBORN MICHIGAN

Revised 1939

Anyone intending to master the fundamentals of electricity should realize that a thorough understanding of equations is essential because they are used extensively in electrical work. Equations are completely understood, however, only when one is familiar with certain fundamentals of algebra. These will be considered first.

POSITIVE AND NEGATIVE NUMBERS.- In arithmetic the + and - signs are merely symbols of operation, which denote addition and subtraction. In algebra their meaning is extended.

The scale of the thermometer extends in both directions from zero, indicating numbers of opposite nature (see fig. 1). The thermometer may indicate 7° above zero or 7° below zero. To distinguish between the two readings it is convenient to call the readings above zero, positive, and those below zero, negative. Then 7 degrees above zero is written +7, and 7 degrees below zero is written -7. Thus we have a new meaning for the + and - signs. They not only indicate addition and subtraction, but also the direction the quantity is from zero. If there is no sign preceding the number, the + sign is understood.

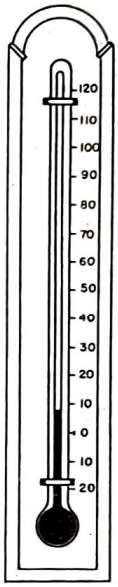


Fig. 1

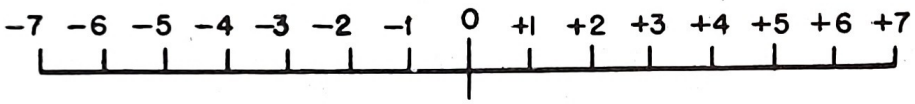


Fig. 2 Number scale

ADDITION.- Algebraic addition is the process of combining positive and negative numbers. This is easily done by means of a number scale, which is shown in fig. 2.

(1) To add +5 and +6, begin at +5 and count 6 units in the positive direction, arriving at +11. Then (+5) + (+6) = +11.

(2) To add -5 and -6, begin at -5 and count 6 units in the negative direction, arriving at -11. Then (-5) + (-6) = -11.

(3) To add -5 and +6, begin at -5 and count 6 units in the positive direction, arriving at +1. Then (-5) + (+6) = (+1).

(4) To add +5 and -6, begin at +5 and count 6 units in the negative direction, arriving at -1. Then (+5) + (-6) = (-1).

These illustrative examples suggest the following rules:

Rule 1. To add two numbers of like signs, add the numbers as in arithmetic and prefix the common sign to the result.

Rule 2. To add two numbers of unlike signs, subtract the smaller from the larger and prefix the sign of the larger number to the result.

When more than two numbers are added, the best procedure is to add all the positive numbers, then all the negative numbers, and then proceed as explained in Rule 2.

SUBTRACTION.- In the illustrative examples on addition, two numbers were given and their sum computed. In subtraction the sum of two numbers and one of the numbers are given. The other number is to be determined. If it is desired to subtract say +2 from +6, determine what number added to +2 gives +6. This procedure may be used with both positive and negative numbers. Thus, subtraction is merely the inverse of addition.

(1) To subtract +2 from +6, begin at +2 and count to +6. Four units in the positive direction are counted. Then (+6) - (+2) = +4.

(2) To subtract -2 from +6, begin at -2 and count to +6. Eight units in the positive direction are counted. Then (+6) - (-2) = +8.

(3) To subtract -6 from -2, begin at -6 and count to -2. Four units in the positive direction are counted. Then (-2) - (-6) = +4.

(4) To subtract -2 from -6, begin at -2 and count to -6. Four units in the negative direction are counted. Then (-6) - (-2) = -4.

In these illustrations note that subtracting any positive or negative number is equivalent to adding the same number with its sign changed.

Rule 3. To subtract one number from another, change the sign of the number to be subtracted and proceed as in addition.

MULTIPLICATION.- Multiplication is merely repeated addition. It is the process of taking one number as many times as there are units in the other. Four possible cases arise.

(1) (+3) × (+5) means add +5 three times, and this gives (+5) + (+5) + (+5) = +15. Then (+3) × (+5) = +15.

(2) (+3) × (-5) means add -5 three times, and this gives (-5) + (-5) + (-5) = -15. Then (+3) × (-5) = -15.

(3) (-3) × (+5) means subtract +5 three times, but subtracting +5 is the same as adding -5 (see Rule 3). Therefore, -(+5) - (+5) - (+5) = (-5) + (-5) + (-5) = -15. Then (-3) × (+5) = -15.

(4) (-3) × (-5) means subtract -5 three times, but subtracting -5 is the same as adding +5. Therefore, - (-5) - (-5) - (-5) = (+5) + (+5) + (+5) = +15.

In these illustrations when both numbers are positive or both negative, their product is positive; when one number is positive and the other is negative, their product is negative.

Rule 4. The product of two numbers with like signs is a positive number, and the product of two numbers with unlike signs is a negative number.

CONTINUED PRODUCTS.- To find the product of three or more numbers, find the product of the first two, and then multiply the result by the third number. Continue this procedure until all the numbers have been used. In an example such as (+2) × (-3) × (-5), +2 is multiplied by -3, giving -6. Their result is then multiplied by -5, giving +30. Changing the order of the multiplication does not change the result.

FACTORS.- A factor of a product is any one of the numbers which multiplied together give the product. In 2 × 3 × 6 = 36, the numbers 2, 3, and 6 are the factors.

HOME WORK

Perform the indicated addition:

1. (+8) + (-4)
2. (-9) + (+6)
3. (-8) + (-2)
4. (+5) + (-12)
5. (-4) + (+7)
6. (-16) + (+7)
7. (+8) + (-2) + (-3)
8. (-4) + (+3) + (-4)

Determine the missing values in the following:

9. (+8) + (?) = +4
10. (-10) + (?) = -17
11. (?) + (+12) = -3
12. (-8) + (?) = 13

Perform the indicated subtraction:

13. (+6) - (+3)
14. (-8) - (+4)
15. (-11) - (-17)
16. (+12) - (-6)
17. (-9) - (+12)
18. (-13) - (+6)

Find the following products:

19. (+3)(-4)
20. (-5)(+8)
21. (8)(-1)
22. (-3)(-2)
23. (+9)(-7)
24. (-3)(-6)
25. (-3)(8)(-2)
26. (-5)(+2)(+4)
27. (-3)(-4)(-6)

In algebra letters are frequently used instead of numbers because by means of letters it is possible to express, in general, the relation between certain quantities regardless of their numerical values. This is best illustrated by means of a few examples.

Example 1.- The cross section of a bus-bar may be found by multiplying its width by its thickness. A may be used to represent the area, W the width, and T the thickness. Then this rule may be expressed as

$$A = W \times T \qquad (1)$$

If W is 1/4 and T is 6, $A = 1/4 \times 6$ or 1-1/2.

Example 2.- The circumference of a circle is found by multiplying 3.1416 by the diameter. This may be expressed as

$$C = 3.1416 \times D \qquad (2)$$

where C = the circumference and D = the diameter.

If D is 5, $C = 3.1416 \times 5 = 15.708$.

If the sign of operation is omitted, multiplication is understood. For instance, the two above rules are generally written A = WT and C = 3.1416D.

ALGEBRAIC EXPRESSIONS.- Any group of numbers and letters joined by signs of operation, such as E - 2R - 10, is called an expression. The parts of an expression connected by plus or minus signs or both are called terms. In the expression E - 2R - 10, the terms are E, -2R, and -10. Terms with like literal factors, such as 51R, 21R, and 31R, are called like terms.

ADDITION AND SUBTRACTION OF LIKE TERMS.- Adding 5 two's, 3 two's, and 10 two's gives 18 two's. This may be expressed as follows:

$$\begin{array}{r} 5 \times 2 \\ 3 \times 2 \\ \underline{10 \times 2} \\ 18 \times 2 \end{array}$$

Using letters instead of the common numbers, we have

$$\begin{array}{r} 5A \\ 3A \\ \underline{10A} \\ 18A \end{array}$$

The common factor A is brought down and the coefficients 5, 3, and 10 are added and the sum written as the coefficient in the answer.

In arithmetic we learned that unlike things, such as 8 batteries and 2 motors, cannot be added. In the same way, unlike terms, such as 8b and 2m, cannot be added; they can only be indicated, as 8b + 2m. Observe the following:

Examples in Addition

4ab	12ab	-16IR
-6ab	4c	3IR
16ab	6ab	5I
14ab	18ab + 4c	-13IR + 5I

Examples in Subtraction

4IR	14ab	16IR
-6IR	-4c	3I
10IR	14ab + 4c	16IR - 3I

Rule 5. Terms with the same literal expression can be added or subtracted by adding or subtracting the numerical coefficient. If the literal expressions are not alike, the operation can only be indicated.

POWERS.- If a number is taken several times as a factor, the number is said to be raised to a power. Thus $2 \times 2 \times 2$ may be expressed a shorter way by writing 2^3, which means that 2 is taken as a factor three times and gives 8. 8 is the third power or cube of 2. 2^3 is read 2 to the third power, or 2 cubed. 2^2 means 2×2 and is read 2 to the second power or 2 squared.

A number written to the right and a little above another number to indicate the number of times the latter is taken as a factor is called an exponent. The exponent 1 is never written since 2^1 is the same as 2.

Exponents may be affixed to letters as well as numbers. Thus aaaa may be expressed a^4. In a term such as $2a^2$, the exponent applies only to the letter. The exponent may be made to apply to the number also by enclosing the letter and number, as $(2a)^2$.

LAW OF EXPONENTS IN MULTIPLICATION.- Since a^2 means aa, and a^3 means aaa, then $a^2 \times a^3 = (aa)(aaa) = a^5$. That is, $a^2 \times a^3 = a^5$. From this and all similar problems the following rule can be stated.

Rule 6. The product of two or more powers of the same base is equal to the base with an exponent equal to the sum of the exponents of the powers.

When terms with different bases are to be multiplied, their product can only be indicated. Thus $a^3 \times y^2 = a^3y^2$. When several different bases occur in each factor, the powers with the same base can be combined. For instance, $2a^2b^3c \times 3a^3b^4d = 2 \times 3a^2a^3b^3b^4cd = 6a^5b^7cd$.

DIVISION.- In the division of positive and negative numbers, the laws of signs and of exponents may be developed from a study of the laws that apply to signs and exponents in multiplication. Division is the inverse of multiplication.

Since $(+4) \times (+3) = +12$, then $(+12) \div (+3) = +4$.

Similarly, since $(-4) \times (+3) = -12$, then $(-12) \div (+3) = -4$.

Also, $(-12) \div (-4) = +3$.

Again, since $(-4) \times (-3) = +12$, then $(+12) \div (-3) = -4$.

From these examples, the law of signs for division may be stated as follows:

Rule 7. The quotient of two numbers with like signs is a positive number, and the quotient of two numbers with unlike signs is a negative number.

LAW OF EXPONENTS IN DIVISION.- Since in multiplication, $a^3a^4 = a^7$, then $a^7 \div a^4 = a^3$, and $a^7 \div a^3 = a^4$.

The division of powers may also be performed by cancellation. Since $a^5 = aaaaa$, and $a^3 = aaa$, then

$$\frac{a^5}{a^3} = \frac{\cancel{a}\cancel{a}\cancel{a}aa}{\cancel{a}\cancel{a}\cancel{a}} = a^2$$

Rule 8. In the division of powers with the same base, the exponent in the quotient equals the exponent in the numerator minus the exponent in the denominator.

When several different bases occur in each factor, the division may be performed by cancellation. Since $8a^3b^2$ means 8aaabb, and $2a^2b$ means 2aab, then

$$\frac{8a^3b^2}{2a^2b} = \frac{\overset{4}{\cancel{8}}\cancel{a}\cancel{a}a\cancel{b}b}{\underset{1}{\cancel{2}}\cancel{a}\cancel{a}\cancel{b}} = 4ab$$

Since this process is too long for rapid work, the quotient should be found by subtracting the exponents. Thus,

$$\frac{8a^3b^2}{2a^2b} = 4a^{3-2}b^{2-1} = 4ab$$

ROOT.- If a quantity can be divided into equal factors, one of the factors is called the square root of the quantity. Since $25 = 5 \times 5$, then 5 is the square root of 25. Square root, which is indicated by the sign $\sqrt{\ }$, is the inverse of the square. For instance, $5^2 = 25$ and $\sqrt{25} = 5$. The expression $\sqrt[3]{\ }$ indicates that the cube root is to be taken, that is, one of the three equal factors, as $\sqrt[3]{27} = \sqrt[3]{3 \times 3 \times 3} = 3$. The roots of a few quantities are given below:

$\sqrt{a^2} = a$; $\sqrt{a^2b^2} = ab$; $\sqrt{9a^2} = 3a$; $\sqrt[3]{64} = 4$; $\sqrt[3]{a^3b^3} = ab$; $\sqrt[3]{8a^3} = 2a$

SUBSCRIPTS.- Different quantities of the same thing are often represented by the same letter with a number or letter to the right and a little below it. For instance, when an equation involves two different diameters, one may be represented by D_1 and the other by D_2. These are read D sub 1 and D sub 2. Other examples are X_L, R_1^2, and $\sqrt{Z_R}$. These are read X sub L, R sub 1 square, and the square root of Z sub R. Subscripts, unlike exponents, possess no numerical significance. They merely indicate that the numerical values of the quantities are different. Thus, R_1 and R_2 may be as different in value as A and B.

HOME WORK

Perform the indicated operation:

1. $(+35I) + (-30I)$
2. $(-16L) - (+2L)$
3. $(+3R) + (-R) + (-7R)$
4. $5a + 7 - 3a$
5. $12xy - 7xy + 3x$
6. $14ac - 9xy + ac - 2xy$
7. If $R = 3$ and $I = 5$, determine the value of R^3, I^2, $5R^2$, and 2^3I.

Multiply:

8. a^7a^3
9. $(2a^2b)(-4abc)$
10. $(xy)(-6xy)$
11. $(4x^2y^2z)(2xy)^3z$
12. $(IR)^2(I^2R^2)R$
13. $a - 3$ by a
14. $E + IR$ by I
15. $m^2 - 2mn + 4n^2$ by $-2mn$
16. $-4a^2 - 10ab + 40a^2$ by $2ab^2$

Perform the indicated division:

17. $(+32) \div (-4)$
18. $(-25) \div (+5)$
19. $(-36) \div (-4)$
20. $(+12a^4b) \div (-3a)$
21. $(-2x^2y) \div (-4xy^2)$
22. $x^5 \div x$
23. $\dfrac{R + Rat}{R}$
24. $\dfrac{16np^2 - 36n^2p^2}{2np^2}$

25. Determine: $\sqrt{9}$; $\sqrt{E^2}$; $\sqrt[3]{27}$; $\sqrt{4a^2}$; $\sqrt{a^2b^2}$; $\sqrt{\dfrac{a^4}{4}}$; $\sqrt[3]{27a^3}$

Simplify the following by combining terms (in problems 28 and 29, first find the L C D and then combine terms):

26. $\dfrac{2x^2y + 3xy^2 - 4x^2y}{2xy}$
27. $\dfrac{x - 5x^3 + 15x^5}{-5x^2}$
28. $\dfrac{3}{a} - \dfrac{5}{2a}$
29. $\dfrac{\dfrac{b}{2c} - \dfrac{4bc}{c^2}}{-\dfrac{b}{c^2}}$

EQUATIONS.- In lesson 1 the circumference of a circle was expressed as C = 3.1416D; similarly, the area of a circle may be expressed as A = .7854D. Rules stated in this way are said to be expressed by an equation. The expressions on the left side of the equal sign are called left members and those on the right side are called right members.

Equations are used extensively in the study of electricity, because they convey in condensed form information that would otherwise be imparted only by means of long and cumbersome rules. Because an equation occupies little space, it is possible for the eye to catch at a glance the rule given. Moreover, it is much easier to remember an equation than a rule expressed in words. Then, too, the equation makes clearer the relation between any quantities in it. To illustrate the last statement, an equation much used in electricity will be considered.

Example.- The twisting effect of a motor (torque) is found by multiplying the developed horsepower by 5252 and dividing by the speed. Expressed by an equation,

$$T = \frac{5252\ HP}{N}$$

where T = torque in pound-feet, HP = horsepower, and N = speed in revolutions per minute. In this equation, if N is kept constant and HP, the quantity in the numerator, is increased, T becomes greater in the same proportion. If HP is kept constant and N, the quantity in the denominator, is increased, T decreases in the same proportion. Then T varies directly as HP and inversely as N.

Rule 9.- A quantity in the numerator of one member varies directly as the quantity in the numerator of the other and inversely as the quantity in the denominator of the other.

It is often necessary to express an equation, such as those given in the electrical course, in different ways in order to fit different needs. For instance, suppose it is desired to determine HP in the above equation when T and N are known. To do this, the equation must be expressed as

$$HP = \frac{TN}{5252}$$

In this case the equation is said to be solved for HP in terms of the other letters.

Solving for a letter in an equation is often necessary, and the rule used is founded upon the following evident principle: If exactly the same operation is performed on the two equal members of an equation, the resulting members will be equal.

This important principle may be expressed otherwise by the following axioms (an axiom is a statement so evident that it requires no proof):

1. The same quantity may be added to both members of an equation without destroying their equality.
2. The same quantity may be subtracted from both members of an equation without destroying their equality.
3. Both members of an equation may be multiplied by the same quantity without destroying their equality.
4. Both members of an equation may be divided by the same quantity without destroying their equality.
5. Both members of an equation may be raised to the same power without destroying their equality.
6. The same root may be extracted of both members of an equation without destroying their equality.

By means of these principles, it is possible to get the letter being solved for on one side of the equal sign and all the other letters on the other side.

EXAMPLE 1.- Solve for E_1 in the equation $E = E_1 + E_2$.

To obtain E_1 alone on one side, E_2 must be subtracted from both members. This gives $E - E_2 = E_1 + E_2 - E_2$. Since $+E_2 - E_2 = 0$, then the equation becomes $E - E_2 = E_1$. The same result is obtained if E_2 is transferred to the opposite member and its sign changed.

Hence, any term may be transposed from one member to the other if its sign is changed.

EXAMPLE 2.- Solve for R in the equation $Z = \sqrt{R^2 + X^2}$

Squaring both sides to eliminate the square root sign gives $Z^2 = R^2 + X^2$. Transposing X^2 to the left member gives $Z^2 - X^2 = R^2$, and taking the square root of both sides gives $\sqrt{Z^2 - X^2} = R$.

EXAMPLE 3.- Solve for B in the equation $F = \frac{8.85BIL}{10^8}$.

Multiplying both members by 10^8 to remove 10^8 from the right member gives $10^8F = 8.85BIL$. Dividing by 8.85IL to remove all quantities except B from the right member,

$$\frac{10^8F}{8.85IL} = B$$

The same result is obtained if 10^8 in the denominator is transferred to the numerator in the opposite member, and if 8.85IL in the numerator is transferred to the denominator in the opposite member.

Hence, in an equation with only one term in each member, any quantity may be transferred from one member to the other if it is transferred from the denominator on one side to the numerator on the other.

If a member has more than one term, a value in its numerator and a like value in its denominator cannot be canceled. For instance, in solving example 1, one is apt to proceed as follows:

Dividing both members by E_2, $\frac{E}{E_2} = \frac{E_1 + E_2}{E_2}$

Canceling the E_2's in the left member, which is incorrect, gives $\frac{E}{E_2} = \frac{E_1 + \cancel{E_2}}{\cancel{E_2}}$

This is incorrect because both E_1 and E_2 in the numerator must be divided by E_2 in the denominator. When cancellation is used, only the E_2 in the numerator is divided by the E_2 in the denominator.

HOME WORK

1. In the equation $H = .057I^2Rt$ explain how t varies with the other letters.

Solve for:

2. y_b when $y_f = y_b - 2m$
3. I when $E_g - IR = E_t$
4. y_s when $y_b = y_sC_s + 1$
5. E_c when $I = \frac{E_a - E_c}{R}$
6. R when $E = IR$
7. L when $X_L = 2\pi fL$
8. N when $f = \frac{PN}{2 \times 60}$
9. C when $X_c = \frac{1}{2\pi fC}$
10. I when $H = .057I^2Rt$
11. X when $Z = \sqrt{R^2 + X^2}$
12. I_p when $I_pE_p = I_sE_s$
13. T_p when $\frac{E_p}{T_p} = \frac{E_s}{T_s}$
14. m when $y_c = \frac{C - 2m}{P}$
15. E_2 when $\frac{T_1}{T_2} = \frac{E_1^2}{E_2^2}$
16. N_s when $S = \frac{N_s - N_r}{N_s}$

In using an equation to solve a problem, the values of all the letters must be known except one. The steps involved in determining the value of this unknown letter are: (1) Removing of fractions by multiplying both members by the least common denominator; (2) Transposing to get all unknown quantities in one member and all known quantities in the other; (3) Collecting like terms; (4) Dividing by the coefficient of the unknown.

EXAMPLE 1.- Determine the value of X if $\frac{1}{6}X - \frac{1}{2} = \frac{3}{4}$.

Multiplying by least common denominator (12), $2X - 6 = 9$

Transposing, $2X = 9 + 6 = 15$

Dividing by the coefficient, $X = \frac{15}{2}$ or $7\frac{1}{2}$

To be certain that the problem is solved correctly, the answer should be tested. This is accomplished by substituting the value obtained for the unknown in the original equation. If the two members become identical, then the solution is correct.

Substituting in the above example, $(\frac{1}{6})(\frac{15}{2}) - \frac{1}{2} = \frac{3}{4}$

Collecting terms in the left member, $\frac{3}{4} = \frac{3}{4}$

EXAMPLE 2.- Find the value of R if $\frac{3R}{2} + 40 = 4R - 7 + \frac{6}{7}R$.

Multiplying by the L C D, which is 14, $21R + 560 = 56R - 98 + 12R$

Transposing, $21R - 56R - 12R = -98 - 560$

Collecting terms, $-47R = -658$

Dividing by the coefficient, $R = 14$

Checking, $\frac{3 \times 14}{2} + 40 = 4 \times 14 - 7 + \frac{6}{7} \times 14$

Collecting terms in each member, $61 = 61$

EXAMPLE 3.- Solve for L if $\frac{7}{2L} = \frac{2}{3} + \frac{4}{3L}$.

Multiplying by the L C D, which is 6L, $21 = 4L + 8$

Transposing, $21 - 8 = 4L$

Collecting terms in the left member, $13 = 4L$ or $4L = 13$

Dividing by the coefficient, $L = \frac{13}{4}$ or $3\frac{1}{4}$

Checking, $\frac{7}{2(\frac{13}{4})} = \frac{2}{3} + \frac{4}{3(\frac{13}{4})}$

Collecting terms, $\frac{14}{13} = \frac{14}{13}$

Determine the value of the unknowns in the following equations:

1. $\frac{3}{5}X = 15$

2. $m - 11m = 48$

3. $2E - 7 + 3E = 28$

4. $15 - I = 5 - 3I$

5. $\frac{4}{3}R - \frac{2}{5}R = \frac{14}{75}$

6. $\frac{S}{2} - 15 = \frac{S}{3}$

7. $3 + .5R = 4.25$

8. $X - 16 + 3X = 0$

9. $\frac{2}{5} = \frac{1}{T}$

10. $10 = \frac{90}{Z^2}$

11. $\frac{27}{2a} = \frac{3}{4}$

12. $\frac{1}{a} + \frac{3}{a} = \frac{4}{5}$

13. $\frac{8 + m}{5} = m$

14. $\frac{13}{2k} + \frac{5}{3k} = \frac{7}{6}$

15. $\frac{2}{2 + m} = \frac{6}{m}$

Determine the missing values underneath the equations:

16. $R = R_1 + R_2 + R_3$

R	R_1	R_2	R_3
14	4		2
16		7	5

19. $H = .057I^2Rt$

H	I	R	t
	5	150	60
250,000		200	20
350,000	25	260	

22. $R_f = R_o + R_oat$

R_f	R_o	a	t
	200	.004	55
50	20	.004	
200		.004	30

17. $I = \frac{E}{R}$

I	E	R
	110	16
5	220	
4		30

20. $S = \frac{N_s - N_r}{N_s}$

S	N_s	N_r
	1200	1140
.03	3600	
5%		570

23. $\frac{1}{R} = \frac{1}{R_1} = \frac{1}{R_2}$

R	R_1	R_2
	8	3
6		12
1	4	

18. $R = \frac{Kl}{(m)}$

R	K	l	(m)
6	10.4	1000	
15	10.4		404
	670	15	102

21. $W = IE$ and $I = \frac{E}{R}$

W	I	E	R
450		110	
	5		55
300			200

24. $T = Fr$ and $HP = \frac{NT}{5252}$

HP	N	T	F	r
	1200	20		1
5	1725			1.5
	850		15	1.5

PARENTHESIS.- The sign most commonly used for grouping is the parenthesis, written ( ). It signifies that the terms, or parts of terms, enclosed are to be treated as a single quantity. The parts enclosed then become a single term or part of a term. Thus, $2(5 + 3)$ means that the quantity $5 + 3$ is to be multiplied by 2, which gives 16. $A + (B + C)$ means that the sum of B and C is to be added to A, and $A - (B + C)$ means that the sum of B and C is to be subtracted from A.

In solving certain equations it is necessary to insert or remove parenthesis.

EXAMPLE 1.- Remove the parenthesis from the expression $X^2 + (-X + 3)$. This means that $-X + 3$ is to be added to X^2.

$$\begin{array}{rr} & X^2 \\ & -X+3 \\ \hline \text{Adding,} & X^2-X+3 \end{array}$$

Therefore, $X^2 + (-X + 3) = X^2 - X + 3$. Note that in the result the sign of X is negative and the sign of 3 is positive, just as they were within the parenthesis.

Rule 10.- Parenthesis preceded by a plus sign may be removed without making any other change.

EXAMPLE 2.- Remove the parenthesis from the expression $X^2 - (-X + 3)$. This means that the quantity $-X + 3$ is to be subtracted from X^2.

$$\begin{array}{rr} & X^2 \\ & -X+3 \\ \hline \text{Subtracting,} & X^2+X-3 \end{array}$$

Therefore, $X^2 - (-X + 3) = X^2 + X - 3$. Note that in the result the signs of X and 3 have changed.

Rule 11.- Parenthesis preceded by a minus sign may be removed if the sign of every term within the parenthesis is changed.

EXAMPLE 3.- Remove the parenthesis and collect like terms in the expression $2(2a - 6b) + (4a - b) - (5a - 4b)$.

When the parenthesis enclosing $2a - 6b$ is removed, each term must be multiplied by 2. When the parenthesis enclosing $4a - b$ is removed, the signs of each of these terms remain as they were, because this parenthesis is preceded by a plus sign. When the parenthesis enclosing $5a - 4b$ is removed, the signs of each of these terms must be changed, because the parenthesis is preceded by a minus sign.

Therefore, $2(2a - 6b) + (4a - b) - (5a - 4b) = 4a - 12b + 4a - b - 5a + 4b = 3a - 9b$.

If terms are placed within parenthesis preceded by a plus sign, their signs must not be changed; if placed within parenthesis preceded by a minus sign, their signs must be changed.

Then $X^2 - X - Y + 3 = X^2 + (-X - Y + 3)$ or $X^2 - (+X + Y - 3)$.

FACTORING.- When an expression consists of several terms all of which contain a common factor, the expression may be written with two factors. On dividing by the common factor the other is obtained.

EXAMPLE.- Determine the two factors in the expression $2ab + 4ab^2 + 8a^2b$. Dividing by the common factor, which is $2ab$, gives $1 + 2b + 4a$. Hence, $2ab + 4ab^2 + 8a^2b = 2ab(1 + 2b + 4a)$.

In some equations, the letter to be solved for occurs more than once. In this case it is necessary to factor out this letter from the terms in which it appears before solving for it.

EXAMPLE.- Solve for I in the equation $E = \sqrt{I^2R^2 + I^2X^2}$.

Factoring out I^2 in the right member gives $E = \sqrt{I^2(R^2 + X^2)} = I\sqrt{R^2 + X^2}$.

Then $$\frac{E}{\sqrt{R^2 + X^2}} = I$$

HOME WORK

Remove the parenthesis and collect like terms:

1. $3a + (5a - 2)$
2. $3a + (-a - 4)$
3. $6R - (2 + 3R)$
4. $9K - (-3K - 1)$
5. $4L - 3(5 - 4L)$
6. $-(x - y) - (2y - x)$

Enclose the last two terms of the following expressions in parenthesis preceded by (a) a plus sign; (b) a minus sign.

7. $a - b + c$
8. $X^2 + X - 10$
9. $R - 5S - S^2$

Write as two factors:

10. $.5I + .5$
11. $R_o + R_oat$
12. $4xy + 8x$
13. $10R^2 + 6R$
14. $\frac{2\pi R_1 - 2\pi R_2}{2}$
15. $\pi R_1^2 - \pi R_2^2$
16. $3x^2y - 6xy^2$
17. $\sqrt{I^2R^2 + I^2X^2}$
18. $\sqrt{(IR)^2 + (IX_L - IX_c)^2}$

In the following equations, which nearly all pertain to electricity, solve for:

19. t when $R_f = R_o + R_oat$
20. F when $C = \frac{5}{9}(F - 32)$
21. N_s when $S = \frac{N_s - N_r}{N_s}$
22. R_i when $R_f = \frac{R_i(1 + at_f)}{1 + at_i}$
23. R_o when $R_f = R_o + R_oat$
24. I when $E = \sqrt{(IR)^2 + (IX)^2}$
25. n when $C = \frac{2248AK(n - 1)}{10^{10}d}$
26. X when $\frac{R_2}{R_1} = \frac{X}{L - X}$

ANOTHER IMPORTANT USE OF EQUATIONS.- One common type of problem is solved as follows: (1) Represent the unknown quantity by a letter. (2) If there are more unknowns than one, express the others in terms of the first. (3) Write an equation from the information given in the problem. (4) Solve for the unknown letter. (5) Solve for the other unknown quantities with the expression written for case 2.

EXAMPLE 1.- A bus-bar must be 24 times as wide as it is thick. What must be its dimensions to be $1\frac{1}{2}$ square inches in cross section?

Let T = its thickness
Then $24T$ = its width
And $(T)(24T) = \frac{3}{2}$
Or $24T^2 = \frac{3}{2}$

$T^2 = \frac{1}{16}$ or $T = \frac{1}{4}$ inch in thickness

$24T = 24 \times \frac{1}{4} = 6$ inches in width

EXAMPLE 2.- A room is 6 feet longer than it is wide. If its perimeter (distance around) is 52 feet, determine its dimensions.

Let W = its width
Then $W + 6$ = its length
And $2W + 2(W + 6)$ = its perimeter
Therefore $2W + 2(W + 6) = 52$ feet
Or $4W = 40$, or $W = 10$ feet in width
$W + 6 = 10 + 6 = 16$ feet in length

HOME WORK

1. A switch and its cover together cost 76 cents. If the switch cost 24 cents more than the cover, how much did each cost?
2. A generator and switch board together cost $8050. If the switchboard cost $2\frac{1}{2}$ times as much as the generator, determine the cost of each.
3. A bus-bar must be 12 times as wide as it is thick. What must be its dimensions to be $2\frac{1}{4}$ square inches in cross section?
4. The length of a rectangle is five times the width, and the perimeter (distance around) is 30 feet. Find the length and width.
5. The average grade made by a student in three subjects is 88. What grade must he make in the fourth subject so that his average is 90?
6. The weight of a motor is $2\frac{1}{2}$ times that of its starter and the weight of the rheostat is one-third the weight of the starter. If the three together weigh 69 lbs, determine the weight of each.
7. A pipe 10 feet long is to be cut so that the first piece is three times as long as the second and the second half as long as the third. Determine the length of each.
8. An electrician can install a switch board in three days and his helper in four days. In how many days can both together install it?

CURVE READING.- Curves are used to show clearly and in little space what would otherwise require numerous words to state. The characteristics of electric machinery are frequently shown in this way. In Fig. 3 is illustrated one application of a curve, which shows how the amount of magnetism produced in an iron core coil varies with the current through it. This curve indicates that with a constant increase in current, the magnetism increases slightly at first, soon rises rapidly until considerable magnetism is produced, and then again increases at a slow rate.

Fig. 4 shows that the terminal voltage of one cell of a fully charged battery is 3.2 volts. As the battery is discharged, the voltage drops very slowly until it reaches about 1.9 volts, and then drops rapidly.

The upper curve shows how the terminal voltage of a battery varies while it is being charged. The voltage rises rapidly at first for a short period, then rises slowly until the battery is fully charged. After this the rise is rapid until a voltage of about 3.2 is reached; then the voltage remains practically constant.

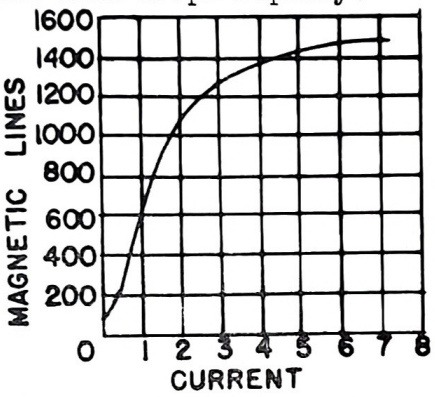


Fig. 3 Variation of the magnetism with the current

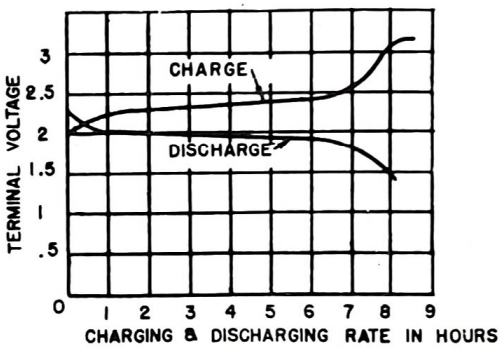


Fig. 4
Variation of battery voltage during charge and discharge

PLOTTING CURVES.- Suppose that it is desired to plot a discharge curve, such as the one shown in Fig. 4, for a particular battery. To obtain the data for plotting the curve, an adjustable resistance is connected across a cell to maintain the rated electric current, and voltage measurements are made every hour. The data obtained is recorded as indicated in Table 1. On the graph of Fig. 5 a point is indicated for each set of readings. Each point is placed on a vertical line corresponding to the time the reading was taken and on a horizontal line corresponding to the voltage. After all the points are marked, a smooth line is drawn through them.

TIME	VOLTS
0	2.3
1	2.1
2	2.
3	1.95
4	1.94
5	1.93
6	1.92
7	1.8
8	1.5

Table 1

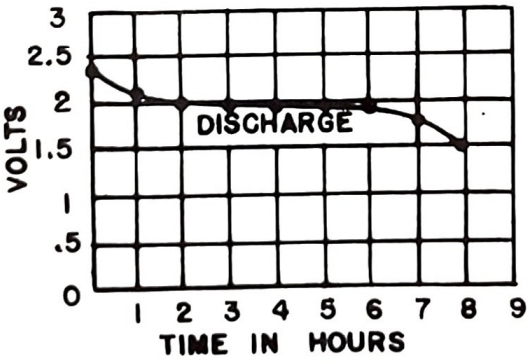


Fig. 5
Plotting a discharge curve

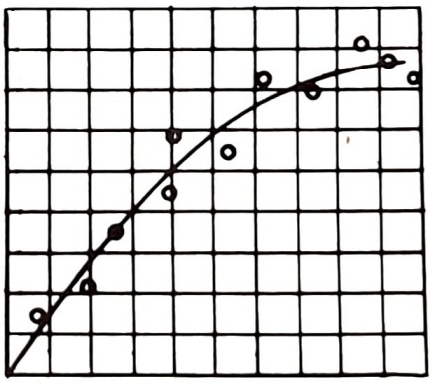


Fig. 6 Plotting curve with inaccurate values

If readings obtained during an experiment are not accurate, a smooth curve cannot be drawn through all the points. In this case the curve should be drawn to give an average of the values. This is illustrated in Fig. 6.

It is sometimes necessary to plot negative as well as positive numbers. As an illustration, suppose two quantities are related according to the equation $y = x + 2$.

By giving x a series of values, a corresponding series of values can be obtained for y. Letting x = 8, then y = 8 + 2 or 10; letting x = 6, then y = 8, etc. Table 2 gives values of y for different values of x.

The type of graph required for plotting negative and positive numbers is shown in Fig. 7. Line x is called the x axis, line y is called the y axis, and the point of intersection 0 of these lines is called the origin. Values to the right of 0 are positive and those to the left of 0 are negative; those upward are positive and those downward are negative. To locate the first point given in Table 2, which is (8, 10), count on the x axis 8 units to the right of the origin and from this point count upward 10 units. This point is shown at P in Fig. 7; the second point is shown at Q; etc.

y	x
10	8
8	6
6	4
4	2
2	0
0	-2
-2	-4
-4	-6
-6	-8

Table 2

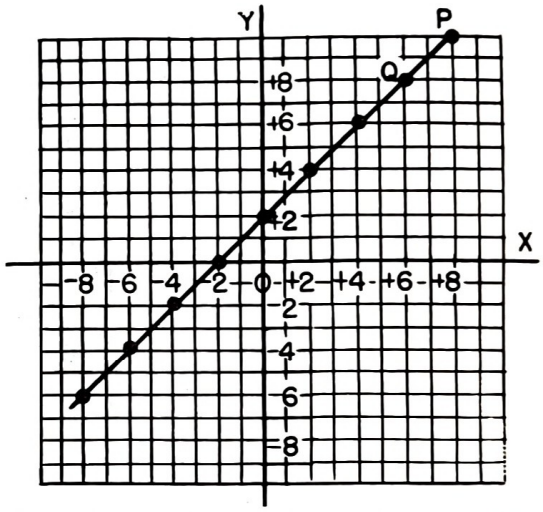


Fig. 7 Graph with negative values

In an equation with two variables, if each term contains only one letter, regardless of how the equation is expressed, the graph plotted from this equation will be a straight line.

HOME WORK

In the following problems use 1/4 inch as the unit of measure.

Plot curves for the values given in the following:

(1)

e	I
0	0
20	.8
40	1.6
60	3
70	4
80	4.5
82	8
80	12

(2)

y	x
15	-6
11	-4
7	-2
3	0
-1	2
-5	4
-9	6

(3)

e	I
5	-6
0	-4
-3	-2
-4	0
-3	2
0	4
5	6

4. Relatively to two axes at right angles to each other, indicate the following points: (5, 2); (0, 4); (3, 0); (-2, 6); (3, -4); and (-2, -4).

Plot the following equations:

5. $y = 2x^2 - 4$

6. $2x + y = 4$

7. $xy = 4$

8. In the following, which equations when plotted give straight lines?

(a) $F = \frac{9}{5}C + 32$

(b) $A = \pi r^2$

(c) $X_c = \frac{1}{377C}$

(d) $6x + 3y = 10$

(e) $y = \frac{1}{x} + 5$

(f) $5 + xy = 8$

It has been known for many years that if sticks of sealing wax are rubbed with wool or if glass rods are rubbed with silk, these materials become electrified (or charged). If two charged sticks of sealing wax or two charged glass rods are brought near each other, repulsion occurs. Attraction occurs, however, if a charged stick of sealing wax is brought near a charged glass rod. This shows that the charge on the sealing wax is different from the charge on the glass. Such a test on other materials reveals either a charge like that found on sealing wax or one like that found on glass. To distinguish these two charges, the one on the sealing wax is called negative and the one on the glass rod is called positive.

The reason that materials become electrified on being rubbed is now known, and this will be explained after the structure of matter has been considered.

STRUCTURE OF MATTER.- Matter is anything that has weight. Any visible quantity of matter contains an inconceivable number of particles called molecules. A molecule is the smallest particle into which a substance can be divided without changing its identity. If the division is carried further, which can be done chemically, each molecule can be divided into two or more particles called atoms. As an illustration, suppose that a certain quantity of water is divided into the smallest parts in which it can exist as water. These parts are called molecules. Each molecule can be further broken up into three atoms, two atoms of hydrogen and one atom of oxygen. Both hydrogen and oxygen are gases, and have entirely different properties from water.

ELECTRONS.- Each atom, in turn, consists of an equal number of protons and electrons. The electrons possess the same kind of charge as the sealing wax and are therefore considered negative. The protons possess the same kind of charge as the glass rod and are therefore positive. All the protons and about half the electrons are concentrated in the central portion of the atom, which is called the nucleus. The remaining electrons (which of course are negative) revolve about the nucleus in definite paths, as the planets revolve about the sun. A model of a copper atom is shown in fig. 1.

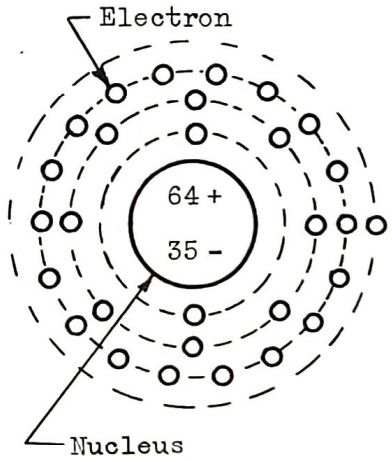
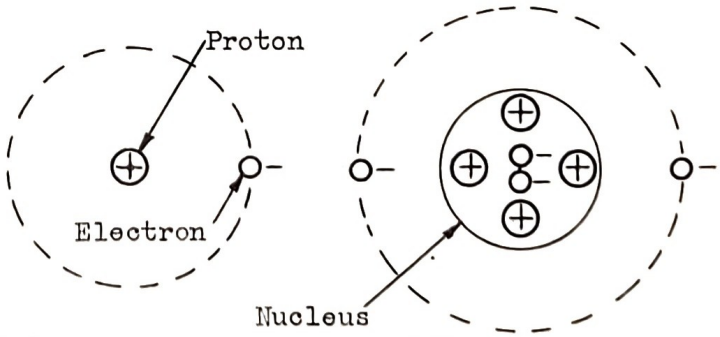


Fig. 1 Copper atom

Electrons are all alike; each weighs $317 \div 10^{31}$ of an ounce and has a diameter of $157 \div 10^{15}$ of an inch. The protons (which are also all alike) each weigh about two thousand times as much as an electron.

KINDS OF ATOMS.- There are actually only 92 different kinds of atoms. The number of external electrons in them varies by one, and the charge on each nucleus varies in proportion. Thus the heavier atoms contain many more electrons and protons than the lighter ones. Hydrogen has the simplest atomic structure, consisting of one proton and one electron (fig. 2a). Next in simplicity is the helium atom, having four protons and two electrons in the nucleus and two external electrons (fig. 2b). Note that in this atom, as well as in all others, the negative and positive charges are just equal. All the elements may be analyzed in this way, finishing with uranium which has 92 external electrons.



(a) Hydrogen atom (b) Helium atom

Fig. 2 Models of atoms

Suppose that some of the external electrons shown in fig. 1 are removed. Then the positive and negative charges are no longer equal. The excess of protons in the nucleus gives the atom a positive charge. If the removed electrons are allowed to return to the nucleus, a neutral atom again results. Thus a positively charged body is one which is deprived of electrons. Apparently, a negatively charged body is one which has an excess of electrons.

The sealing wax became negative when it was rubbed because electrons were deposited upon it after they left the fur. If the fur is tested it will be found to have a positive charge or a lack of electrons. The glass rod rubbed with silk became positive because the electrons left it and were deposited upon the silk. Therefore, whenever a material has an excess of electrons it is negatively charged, and when it has a lack of electrons it is positively charged.

DIRECTION OF ELECTRONS IN A CONDUCTOR.- In non-metallic materials, such as rubber and glass, the electrons are held rather rigidly to their nuclei. But in metals, such as copper and iron, some of the electrons are held loosely to their nuclei and can be made to flow. These are called free electrons.

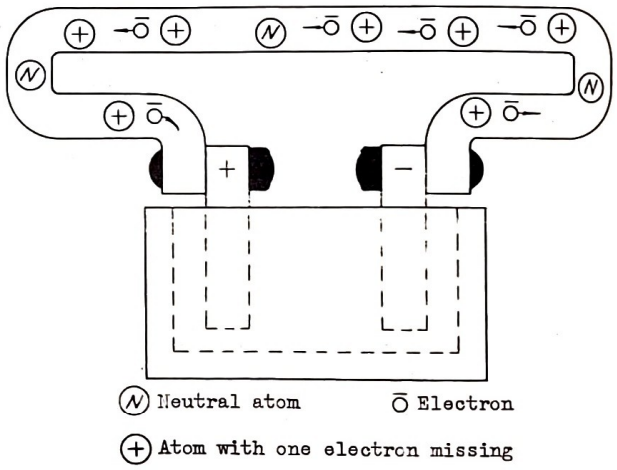


Fig. 3
Conductor carrying an electric current

Suppose that a heavy copper wire or some other material that has free electrons is connected to the terminals of a battery (fig. 3), making one end of the wire positive and the other negative. The free electrons will be attracted toward the positive terminal and will be repelled from the negative terminal. This will cause the electrons to drift toward the positive. They next pass through the battery, then again through the wire, and so on. This flow of electrons constitutes an electric current. The current through a small lamp is about 10^{18} electrons per second. In a wire the electrons move from negative to positive and this flow constitutes an electric current. The early experimenters, not knowing the actual direction of flow, arbitrarily assumed it to be from positive to negative. Due to this unfortunate circumstance, it is necessary to accustom ourselves to thinking that the current flow is in the opposite direction to the flow of electrons.

AMPERE.- To specify the rate at which water is flowing through a pipe, the unit of measure called the gallon is used and the rate is specified in gallons per second. Similarly, to specify the rate at which an electric current flows through a conductor, a unit of measure called the coulomb is used and the rate is specified in coulombs per second, which is the flow of 628×10^{16} electrons per second. The expression "coulomb per second" is seldom used in practice. Instead, a shorter term, which is "ampere", is generally used and means the same thing. Then it is unnecessary to say "per second" because ampere means coulombs per second. The relation between the coulomb and the ampere may be expressed as

$$Q = It \qquad (1)$$

where Q = quantity of coulombs, I = current in amperes, and t = time in seconds.

EXAMPLE.- A battery sends a current of 10 amperes through a circuit for one hour. (a) How many coulombs will flow through the circuit? (b) How many electrons per second?

(a) $Q = 10 \times 3600 = 36{,}000$ coulombs

(b) $10 \times 628 \times 10^{16} = 268 \times 10^{17}$ electrons per second

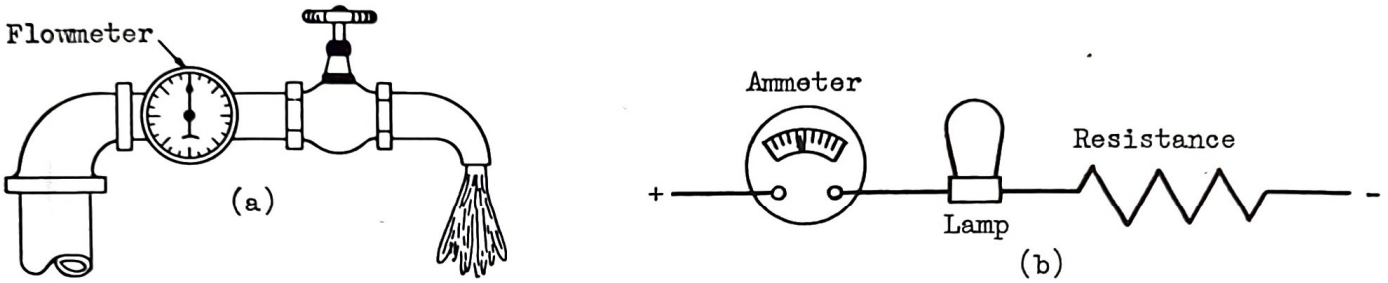


Fig. 4 Current measurement

CURRENT MEASUREMENT.- To measure the flow of water through a pipe, a flow meter must be inserted into the pipe through which the water flows, as shown in fig. 4a, so that all the water flowing through the pipe also flows through the meter.

In like manner, to measure the flow of current through a wire, a current meter (called an ammeter) must be inserted into the circuit so that all the current to be measured flows through the instrument (fig. 4b). The ammeter has a low resistance so as not to hinder the flow of current. Its principle of operation, and that of other indicating instruments, will be studied starting with lesson 105.

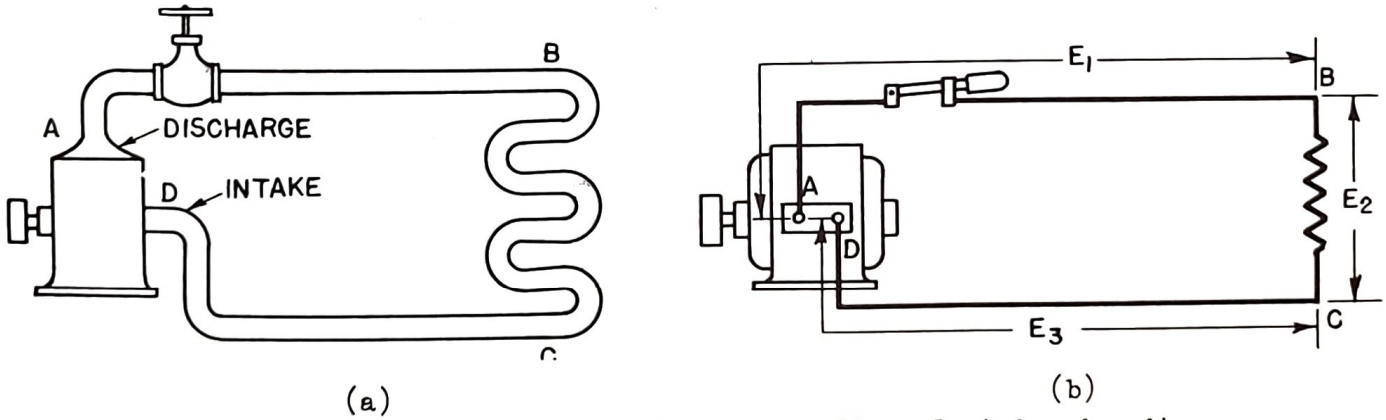


Fig. 5 Hydraulic circuit and corresponding electric circuit

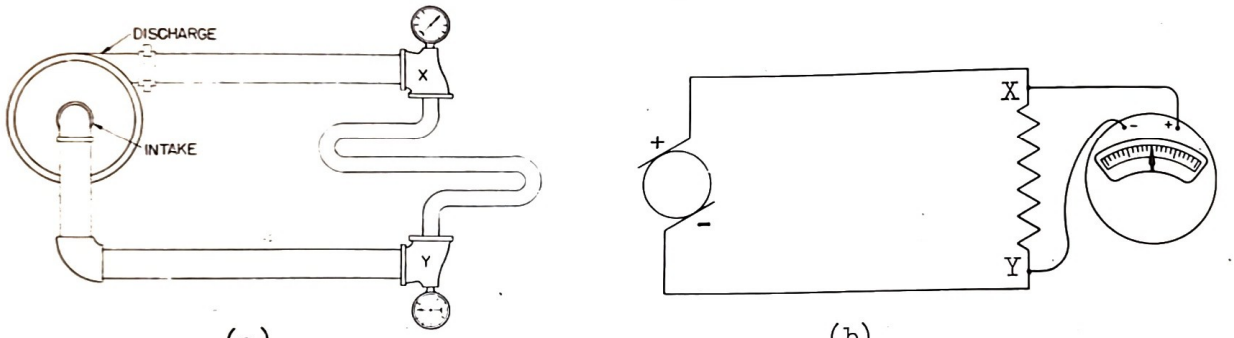
VOLTAGE.- In fig. 5a the action of the blades causes the water to enter the pump at D at a low pressure and leave at A at a high pressure. Section AB has little friction, and the pressure at B is therefore only slightly less than at A, say 5 pounds per square inch. Section BC has considerable friction, and the pressure at C is therefore considerably less than at B, say 100 pounds per square inch. CD has the same friction as AB and therefore the same drop in pressure. The drop in pressure from A to D along the pipe line is 5 + 100 + 5 or 110 pounds per square inch, which equals the pressure difference supplied by the pump.

A similar condition exists in an electric circuit, where the pressure drops are expressed in "volts." The unit "volt" is used in an electric circuit just as the unit "pounds per square inch" is used in the hydraulic circuit. Referring to fig. 5b, the section of the wire from A to B has a low resistance and the pressure drop is low, say 5 volts. BC has a high resistance and the drop is therefore high, say 100 volts.

CD has the same resistance as AB and therefore has the same pressure drop. The drop in pressure along the conductor is 5 + 100 + 5 or 110 volts, which equals the pressure difference supplied by the generator.

In an electric circuit, the term "electromotive force" (denoted by e m f) is used to indicate the voltage generated at the source, such as that developed by a battery or a generator. The term "voltage drop" is used to denote the drop in pressure in a particular part of a circuit. In fig. 5b or in any other series circuit, if E equals the supplied voltage and E_1, E_2, and E_3 equal the voltage drops in the sections, then

$$E = E_1 + E_2 + E_3 \qquad (2)$$



(a) (b)

Fig. 6 Method of measuring difference of potential

VOLTAGE MEASUREMENT.- The amount of water flowing through a pipe (say pipe XY in fig. 6a) depends upon the pressure difference between the two ends. To measure this difference it is necessary to tap a pressure gage at each end of the pipe as shown. The difference in the two readings will be the resultant pressure effective in forcing water through the pipe.

Similarly, the amount of current flowing through a conductor (say conductor XY in fig. 6b) depends upon the pressure difference (voltage) between the two ends. To measure this difference, it is necessary to tap the voltmeter leads to the ends (X and Y) of the wire. The voltmeter indicates the pressure difference between its ends. It will therefore indicate the voltage across wire XY.

RESISTANCE.- As previously stated, some materials have an abundance of free electrons, which require a low pressure to move them from atom to atom, and establish a high current. Such materials are known as good conductors. Other materials have few free electrons. In these the same electric pressure can move only a few electrons from atom to atom, establishing a low current. These are considered poor conductors. The progressive motion of free electrons is hindered in all materials, because they collide with the atoms of the substance used. The opposition to the flow of electrons (due to the bonds between protons and electrons, as well as to collisions) is called electrical resistance. The methods of computing resistance will be considered later.

There are two common methods of avoiding the use of very large or very small numbers. The first is to group a definite number of small units and call the group by a new name. For example, 12 inches are grouped and known as one foot, three feet become one yard, 5280 feet equal one mile, etc. The second method is to attach a prefix, denoting the quantity, to the name of the unit. This is best illustrated by the list on the right.

QUANTITY	PREFIX	EXAMPLE
1000	Kilo	Kilowatt
1,000,000	Mega	Megavolt
.000001	Micro	Microampere
.001	Milli	Milliampere

1. Define the following: (a) molecule, (b) atom, (c) electron, (d) free electron,

2. What is the difference between atoms of different substances?

3. What is meant by resistance? What causes it?

4. What is an ohm? A megohm? A microhm?

5. What is meant by an ampere? A milliampere? A microampere?

6. What is meant by a volt? A millivolt? A microvolt?

7. Explain voltage, current, and resistance by a water analogy.

8. Find the number of coulombs passing through a 20 ampere motor running for 10 minutes.

9. If a storage battery supplies 900 coulombs in five minutes to a constant load, how much current is it delivering?

10. It takes 360,000 coulombs to charge a certain storage battery. If the charging rate is 15 amperes, how long will it take to fully charge the battery?

11. Why is an electric current assumed to flow in a direction opposite to that in which it actually flows?

12. Why is copper such a good conductor of electricity and mica such a poor one?

OHM'S LAW.- The amount of current flowing through a circuit is directly proportional to the electromotive force or voltage and inversely proportional to the resistance of the circuit. This relationship is called Ohm's law and is expressed as

$$I = \frac{E}{R} \qquad (3)$$

where I = current in amperes, E = electromotive force in volts, and R = resistance in ohms.

EXAMPLE.- How much current does a 30 ohm heater take if the applied e m f is 120 volts?

$$I = \frac{120}{30} = 4 \text{ amperes}$$

EXAMPLE.- Find the resistance of the electric iron shown in fig. 7 if the current flowing is 3 amperes.

$$R = \frac{E}{I} = \frac{120}{3} = 40 \text{ ohms}$$

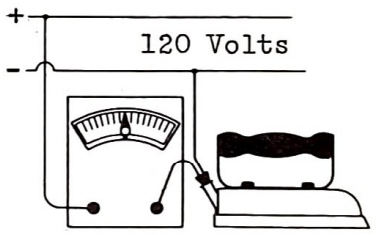


Fig. 7
An electric iron

Ohm's law may be applied to a circuit as a whole or to any of its parts. This may be stated as follows:

(a) The total current flowing in a circuit equals the total voltage applied to the circuit divided by the total resistance of the circuit.

(b) The current flowing in a part of a circuit equals the voltage applied to that part divided by the resistance of that part.

Fig. 8 Series hydraulic circuit and corresponding electric circuit

SERIES CIRCUIT.- If several electrical appliances are connected end to end to form one path for the flow of an electric current (fig. 8a), they are said to be in series. The laws of series circuits can be illustrated by the hydraulic analogy of fig. 8b, which shows pipes of different diameters connected together. The same number of gallons per second must flow through each pipe, regardless of its size, because the water that flows through one pipe must also flow through the others.

Similarly, in the series circuit shown in fig. 8a, no greater current can flow through the ammeter than flows through the lamp and resistor, even though the resistance of the ammeter is much less. Then the current is the same in all the parts.

LAWS OF A SERIES CIRCUIT.- In a series circuit, the following laws apply:

(1) The current is the same in all parts of the circuit.

(2) The total voltage equals the sum of the voltages across the different parts of the circuit. This was expressed by equation 2, which is as follows:

$$E = E_1 + E_2 + E_3 \qquad (4)$$

(3) Applying Ohm's law to the whole circuit shown in fig. 9,

$$E = IR \tag{5}$$

Expressing the voltage drop across the various parts,

$$E_1 = IR_1,\ E_2 = IR_2,\ E_3 = IR_3 \tag{6}$$

Substituting 5 and 6 into 4,

$$IR = IR_1 + IR_2 + IR_3$$

Dividing both members of the equation by I,

$$R = R_1 + R_2 + R_3 \tag{7}$$

Thus, in a series circuit the total resistance equals the sum of the resistances of the separate parts.

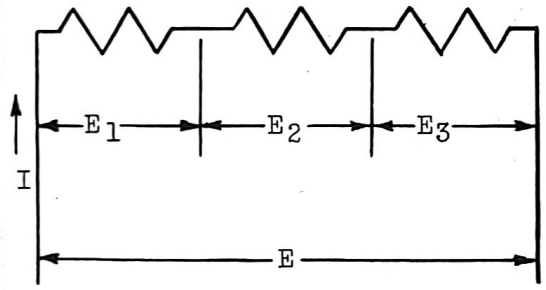


Fig. 9
Resistances in series

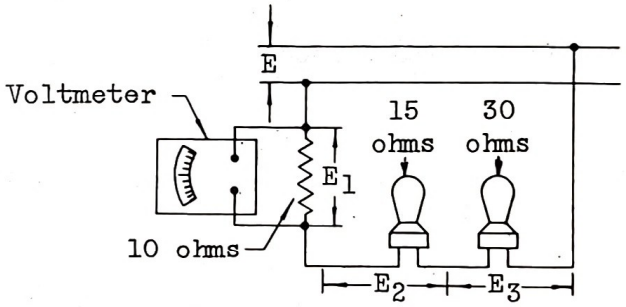


Fig. 10
Voltmeter indicating the voltage drop across a resistor in a series circuit

EXAMPLE.- What voltage must be supplied by a generator to force 2 amperes through a series circuit consisting of a 100 ohm lamp, a 20 ohm resistor, and a 40 ohm soldering iron.

$$R = 100 + 20 + 40 = 160 \text{ ohms}$$

$$E = 2 \times 160 = 320 \text{ volts}$$

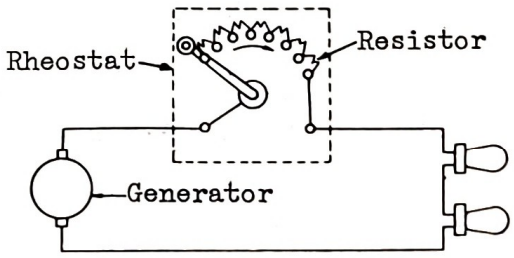


Fig. 11
Rheostat for regulating current

EXAMPLE.- Determine the line voltage (E) in fig. 10 if the voltmeter indicates 20 volts.

The current through the 10 ohm resistor is 20 ÷ 10 or 2 amperes. The two lamps are in series with the conductor and therefore 2 amperes must also pass through them. Then

$$E_2 = 2 \times 15 = 30 \text{ volts}$$

$$E_3 = 2 \times 30 = 60 \text{ volts}$$

$$E = 20 + 30 + 60 = 110 \text{ volts}$$

The most common method of regulating the amount of current supplied to an appliance is to vary the amount of resistance in the circuit. This may be accomplished, without opening the circuit, by means of a rheostat. One common type of rheostat is shown in fig. 11. It consists of series resistors connected to segments over which a contact arm is moved. When the contact arm is in the position shown, all the resistors are in series with the load and the current is low. When the arm is moved to the right, resistors are cut out of the circuit and more current flows. Thus the current may be regulated by shifting the arm.

HOME WORK

1. Write Ohm's law three ways.

2. A voltmeter, which has a resistance of 10,000 ohms, indicates 120 volts. How much current passes through it?

3. A soldering iron connected to a 120 volt line takes 2.5 amperes. What is its resistance?

4. What is the voltage drop in a rheostat if its resistance is 100 ohms and .2 of an ampere flows through it?

5. How much current flows through a 100 ohm lamp and a 160 ohm lamp connected in series to a 120 volt line?

6. A 30 ohm resistor, a 100 ohm lamp, and a 150 ohm lamp are connected in series. If there is a 60 volt drop in the resistor, determine the supplied voltage.

7. A 13,000 ohm voltmeter and a 17,000 ohm voltmeter are connected in series across a 550 volt line. What will each indicate?

8. How much resistance must be connected in series with a 50 ohm lamp, rated at 2 amperes, if it is to be used on a 120 volt line?

9. An arc lamp takes 12 amperes at 120 volts. How much resistance must be connected in series with it to reduce the current to 5 amperes.

10. A 4 ohm, a 6 ohm, and a 7 ohm cast iron grid resistor are connected in series and take 10 amperes. How much additional resistance must be connected in the circuit to reduce the current to 8 amperes, if the supplied voltage remains unchanged?

11. A 23 ohm, a 30 ohm, and an 80 ohm appliance are connected to a 250 volt generator. If the current supplied by the generator is 1.8 amperes, determine the resistance of the connecting wires.

CURRENT IN A PARALLEL CIRCUIT.- A parallel circuit is a circuit that has two or more paths through which the current flows. Fig. 12a shows a hydraulic parallel circuit. The water flows out of the pump to X and there divides, flowing through pipes a, b, and c. Flowing out at Y, it returns to the pump, etc. Of course, the number of gallons per second flowing in at X must equal the sum of the gallons per second through pipes a, b, and c.

The electric circuit shown in fig. 12b may be analyzed similarly. The electric current flows from the generator to X and there divides, flowing through conductors a, b, and c. It then flows out at Y and returns to the generator, etc. As in the hydraulic circuit, the current flowing in at X must equal the sum of the currents flowing through conductors a, b, and c. This may be expressed as follows:

$$I = I_1 + I_2 + I_3 \tag{8}$$

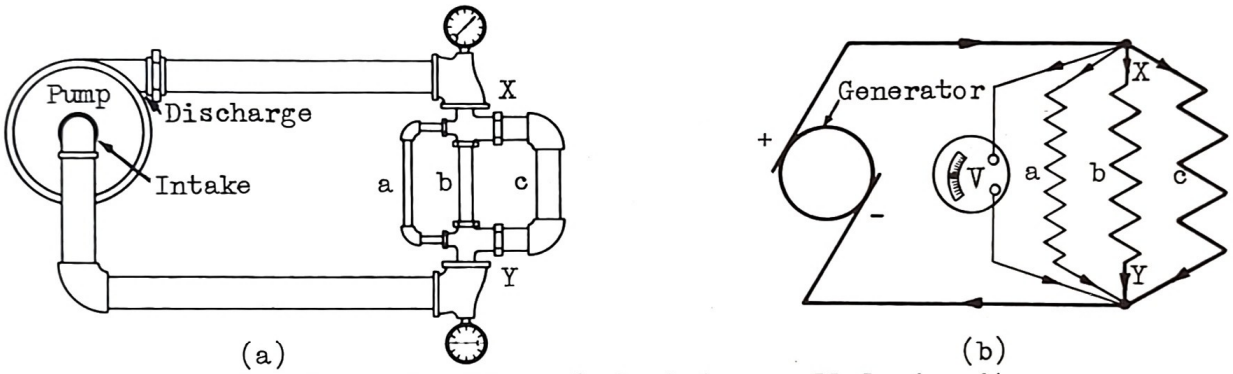


Fig. 12 Hydraulic and electric parallel circuits

VOLTAGE IN A PARALLEL CIRCUIT.- The pressure drop across the three parallel pipes in fig. 12a is found by subtracting the gage reading at Y from the gage reading at X. This gives the drop in pressure across the three pipes in parallel, or across any one of them. If the pressure at one end of pipe a is 120 pounds per square inch and at the other end is 10 pounds per square inch, the drop in pressure across this branch is 110 pounds per square inch. The drop in pressure across the other two branches must be the same as it is across pipe a, because they are connected between the same two points.

Similarly, if the voltage drop across conductor a in fig. 12b is 110 volts, the voltage drop across the other two paths must be the same as the drop across a.

LAWS OF PARALLEL CIRCUITS.- In a parallel circuit, the following laws apply:

(1) The total current supplied to the system equals the sum of the currents through the several paths. This was expressed by equation 8.

(2) The voltage across a parallel combination is the same as the voltage across each branch.

(3) Applying Ohm's law to the circuit of fig. 13, as a whole,

$$I = \frac{E}{R} \tag{9}$$

Applying Ohm's law to the individual paths,

$$I_1 = \frac{E}{R_1},\quad I_2 = \frac{E}{R_2},\quad I_3 = \frac{E}{R_3} \tag{10}$$

Substituting 9 and 10 into 8,

$$\frac{E}{R} = \frac{E}{R_1} + \frac{E}{R_2} + \frac{E}{R_3}$$

Dividing both members of the equation by E,

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \qquad (11)$$

Thus, in a parallel circuit, the reciprocal of the total resistance equals the sum of the reciprocals of the resistances of the individual branches.

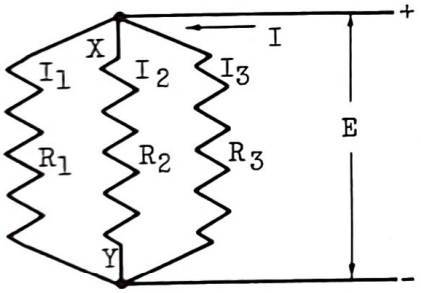


Fig. 13 Combined resistance in a parallel circuit

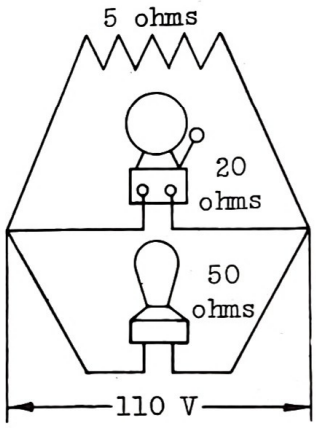


Fig. 14 Finding combined resistance of a parallel circuit

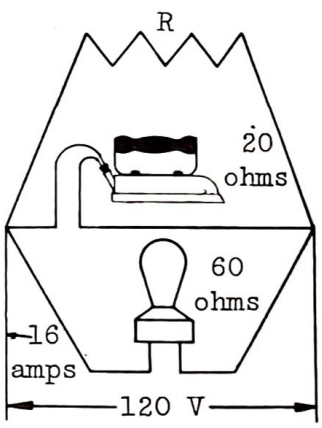


Fig. 15 Finding resistance of one branch of a parallel circuit

EXAMPLE.- Find (a) the combined resistance and (b) the total current taken by the circuit shown in fig. 14.

$$(a)\quad \frac{1}{R} = \frac{1}{5} + \frac{1}{20} + \frac{1}{50} = \frac{27}{100}$$

$$R = \frac{100}{27} = 3.7 \text{ ohms}$$

$$(b)\quad I = \frac{110}{3.7} = 29.7 \text{ amperes}$$

EXAMPLE.- Find the value of R in fig. 15.

The voltage across R is 120. Before the resistance of R can be determined, the current through it must be found, and that can be done only after the current through the other two branches is known. The current through the 20 ohm branch is 120 ÷ 20 or 6 amperes, and the current through the 60 ohm branch is 120 ÷ 60 or 2 amperes. Then the current through R is 16 - 6 - 2 or 8 amperes. Then R = 120 ÷ 8 = 15 ohms.

If the resistances of the branches in a parallel circuit are equal, the total resistance may be found by dividing the resistance of one branch by the number of branches.

EXAMPLE.- Five lamps are connected in parallel across a 120 volt line. If each lamp has a resistance of 200 ohms, determine their combined resistance.

$$R = \frac{200}{5} = 40 \text{ ohms}$$

HOME WORK

1. Five lamps of equal resistances are connected in parallel across a 120 volt line. If they take 3 amperes, what is the resistance of each?

2. Three heating elements having resistances of 30, 60, and 80 ohms are connected in parallel. If a current of 8 amperes flows through the 30 ohm branch, determine the current through each of the other two branches.

3. An unknown resistance, a resistance of 15 ohms, and a resistance of 20 ohms are connected in parallel across a 120 volt generator. If the generator supplies 22 amperes, determine the value of the unknown resistance.

4. What is the combined resistance of a 30 ohm and a 75 ohm cast iron grid resistor connected in parallel?

5. The combined resistance of two lamps in parallel is 80 ohms. If the resistance of one is 200 ohms, what is the resistance of the other?

6. What voltage will be required to force a current of 10 amperes through a 16 ohm resistor and a 20 ohm resistor connected in parallel?

7. The current through a 4 ohm coil and an 8 ohm coil connected in parallel is 10 amperes. Determine (a) the voltage across the coils and (b) the current through each coil.

8. Three lamps having resistances of 60, 80, and 100 ohms are connected in parallel. If the current through them is 8 amperes, determine the current through each.

9. Three equal resistors connected in series have a combined resistance of 25 ohms. What would be their combined resistance if they were connected in parallel?

SERIES-PARALLEL CIRCUITS.- Only simple series and simple parallel circuits have been considered thus far. A combination of series and parallel circuits often exists, however, and a particular arrangement is sometimes complicated. In solving such problems, it should be remembered that any number of resistances in series can be replaced by one resistance having a value equal to the sum of the individual resistances. Also, any number of resistances in parallel can be replaced by a resistance having a value equal to the reciprocal of the sum of the reciprocals of the individual resistances.

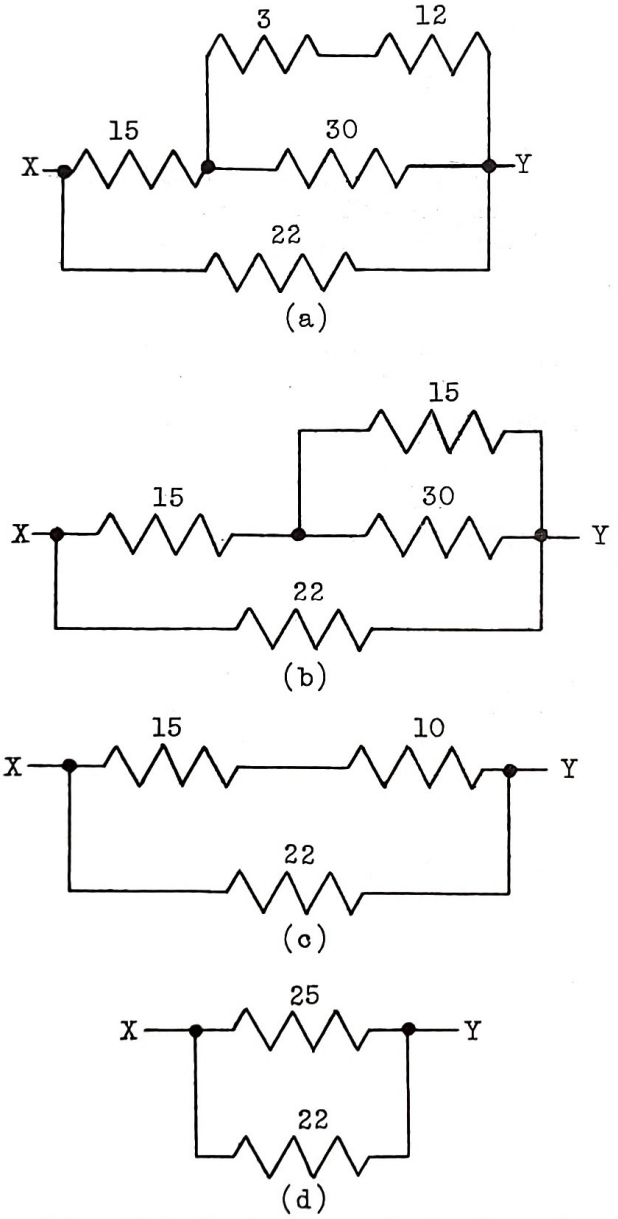
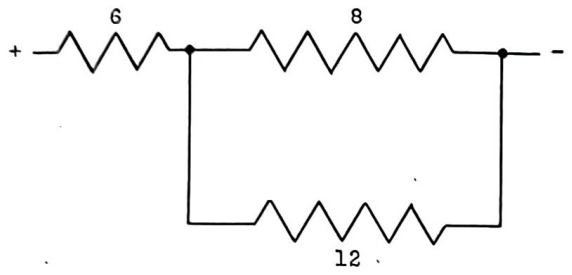


Fig. 16 Series-parallel circuit

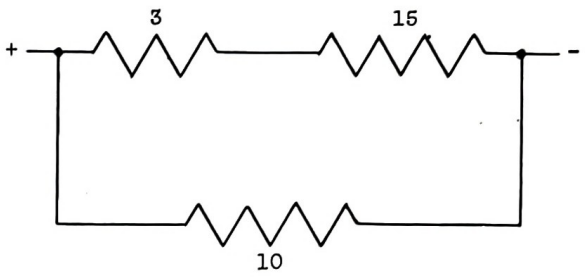
EXAMPLE.- Determine the combined resistance of the circuit shown in fig. 16a. The 3 ohm resistance and the 12 ohm resistance are in series and may be replaced by a 15 ohm resistance (fig. 16b). Now a 15 ohm resistance and a 30 ohm resistance are in parallel, and these may be replaced by a 10 ohm resistance (fig. 16c). The circuit then has a 10 ohm resistance and a 15 ohm resistance in series, which may be replaced by a 25 ohm resistance (fig. 16d). Ultimately, a 25 ohm resistance and a 22 ohm resistance are in parallel, which are combined to give 11.7 ohms.

Find the total resistance in each of the following:

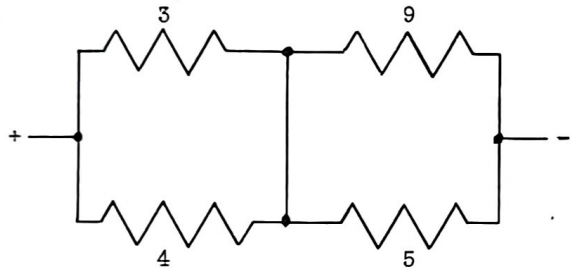
(1)



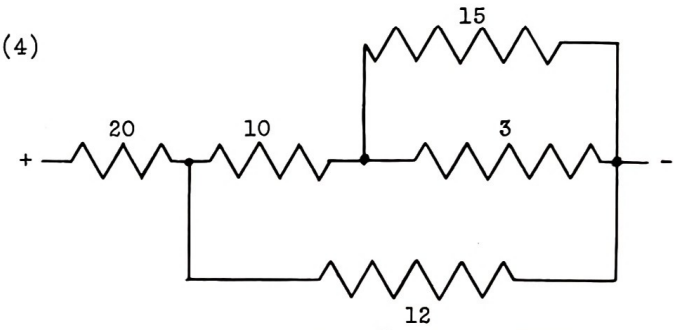
(2)



(3)

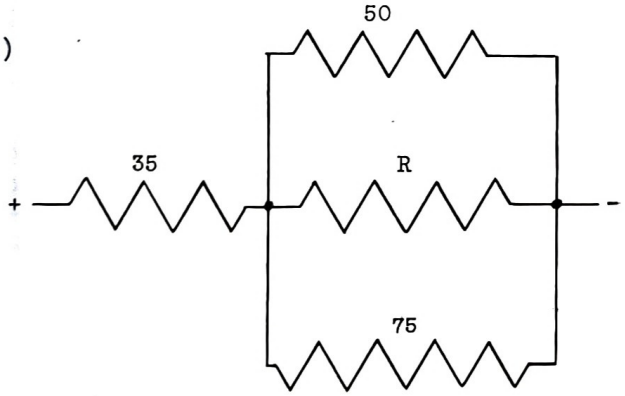


(4)



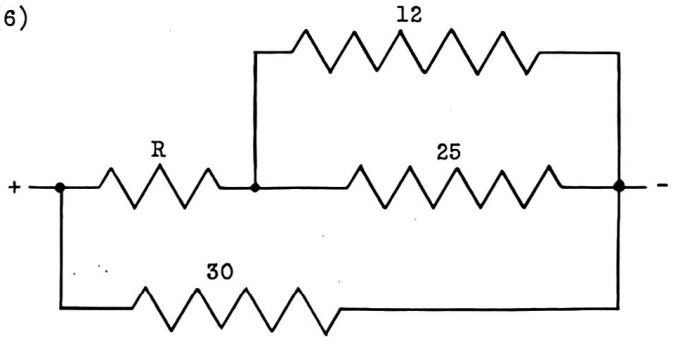
Find the value of R in each of the following:

(5)



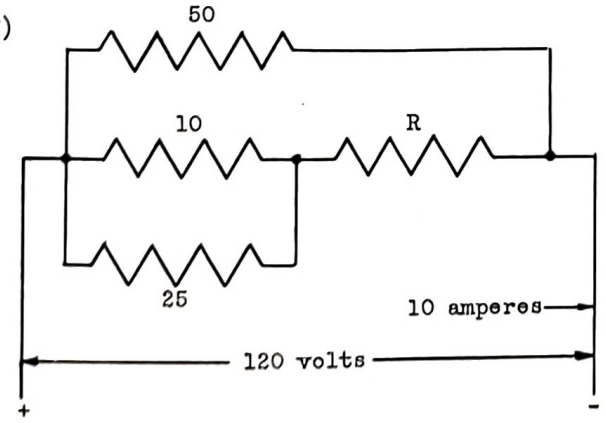
Total resistance = 50 ohms

(6)

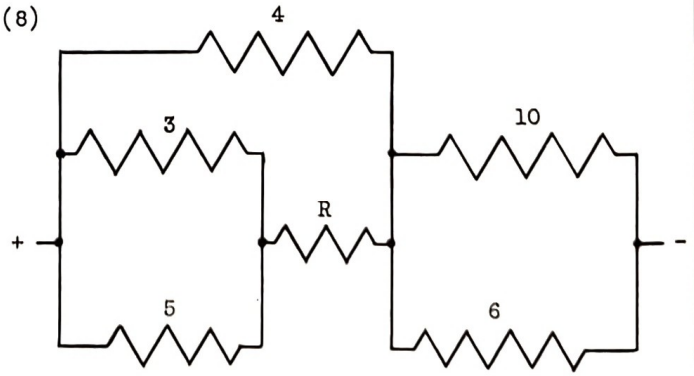


Total resistance = 16 ohms

(7)



(8)



Total resistance = 6 ohms

Incandescent lamps, designed for indoor lighting, are usually connected in parallel. The resistance of any two lamps, even of the same make, is seldom the same; neither is the voltage across each lamp connected to the line the same. However, for convenience in calculating the voltage drop in the line wires, it is the practice to assume that lamps of the same rating take the same amount of current. The error introduced in making this assumption is negligible.

Fig. 18 Current and voltage distribution in a series-parallel circuit

In practice, the simple series circuit and simple parallel circuit seldom occur, but such connections are found in various parts of more complicated systems. By considering each of these parts separately and applying Ohm's law and Kirchhoff's laws, it is usually not difficult to find the current, voltage, and resistance of each part in a system. The method of doing this will be made clear by several examples.

EXAMPLE 1.- In the lighting system shown in fig. 18a, each lamp takes .8 ampere at 120 volts. Find the voltage supplied by the generator.

It is apparent that the three lamps are in parallel and that this combination is in series with the two line wires AB and CD. Then the current through this parallel combination is 3 × .8 or 2.4 amperes. Since the two line wires AB and CD are in series with the parallel combination, the 2.4 amperes also flow through these wires. This current distribution is shown in fig. 18b. The drop in voltage (IR drop) in each of the two sections AB and CD is 2.4 × .5 = 1.2 volts. The voltage across the three parts in series is now known. The voltage across the entire series system equals the sum of the voltages across the separate parts, which is 1.2 + 120 + 1.2 = 122.4 volts. Thus the generator must supply 122.4 volts to force the current through the line wires and lamps.

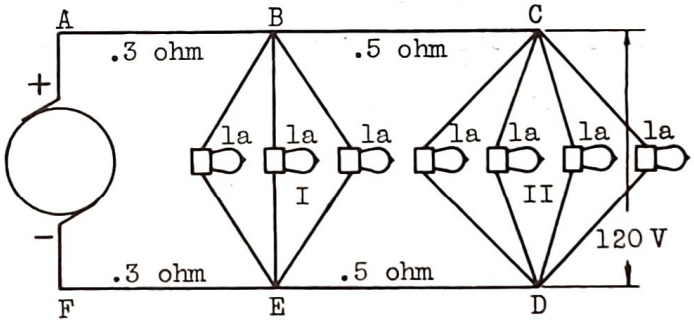


Fig. 19 Simple lighting system

When solving problems of this nature, proceed as follows: First, find the current through each section of the circuit; second, find the voltage across each section; and third, combine the voltages according to the rule for a series circuit.

EXAMPLE.- If each lamp in fig. 19 takes 1 ampere, determine what the voltage across the generator must be to produce 120 volts across the group of lamps located more distant from the generator.

To determine the current through the various sections of a complex system, it is usually more convenient to begin with the lamps farthest from the generator.

Thus, in fig. 19, group II requires 4 amperes. Therefore sections BC and DE must also carry 4 amperes. Group I requires 3 amperes. Then the section AB must carry sufficient current to supply 4 amperes to group II and 3 amperes to group I, which is a total of 4 + 3 or 7 amperes. The 3 amperes leaving group I and the 4 amperes leaving group II pass through section EF. This section, then, must also carry 7 amperes. The current distribution is shown in fig. 20.

The IR drop in each section must now be determined. Since BC and DE each have a resistance of .5 ohm, 4 × .5 or 2 volts are required to force the 4 amperes through each section. Since there are 120 volts across group II, then there must be 120 + 2 + 2 = 124 volts across group I. The voltage required to force 7 amperes through each of the .3 ohm sections, AB and EF, is 7 × .3 = 2.1 volts. The e m f at the terminals of the generator must be 2.1 + 124 + 2.1 = 128.2 volts.

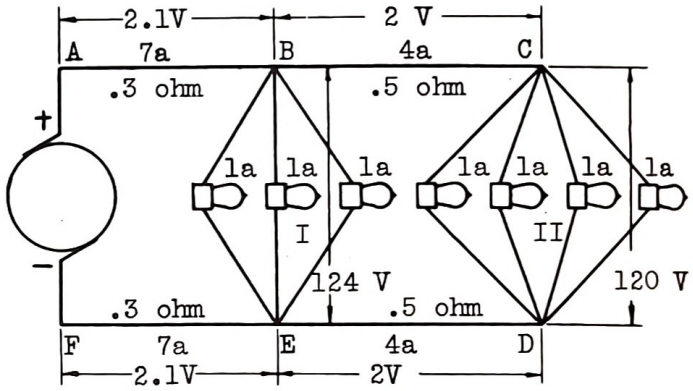


Fig. 20
Current and voltage distribution of the lighting system shown in fig. 19

EXAMPLE 3.- Fig. 21 shows a trolley line fed by two 550 volt generators, one at each end. Two cars are on the line at the points indicated. Car I takes 250 amperes and car II takes 200 amperes. The resistance of the trolley and track are as marked. Find the voltage across each car.

Assume that current flows through the various sections as shown. In the solution, if a current has a negative value the assumed direction is wrong and the arrow should be reversed. However, the numerical value of the current is correct.

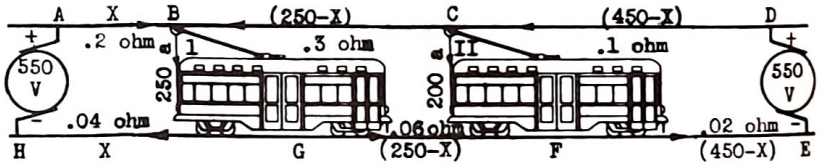


Fig. 21
Current supplied by generators at each end of a trolley line

Let X represent the current through section AB. Since the same current flows through GH, this current may also be represented by X. From Kirchhoff's law the current in sections BC and FG is (250 - X) amperes and the current in sections CD and EF is (450 - X) amperes.

The voltage across car I is 550 - .24X. This voltage is also equal to 550 - .12(450 - X) - .36(250 - X). Then 550 - .24X = 550 - .12(450 - X) - .36(250 - X).

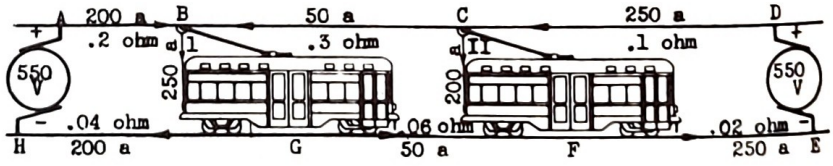


Fig. 22
Current and voltage distribution of trolley car system shown in fig. 21

Solving for the unknown, X = 200 amperes (current through sections AB and GH). It is now an easy matter to find the current in the remaining sections (these are indicated in fig. 22).

The voltage across car I is 550 - (.24 × 200) = 502 volts. The voltage across car II is 502 + (.36 × 50) = 520 volts.

A large variety of mesh-work problems may be solved by using these principles.

1. In the circuit of fig. 14a each lamp takes (A) amperes. Compute (a) the voltage drop in each line wire, and (b) the voltage across each lamp.

2. If the pressure across the generator of fig. 14b is (B) volts, (a) what will be the voltage across lamp L_1, and (b) the voltage across lamp L_2?

3. If a current of (C) amperes flows through each lamp in the circuit of fig. 14, (a) what current flows through each line wire; (b) what is the voltage across each lamp; (c) what is the voltage across the generator?

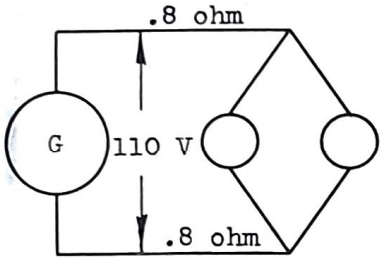


Fig. 14a

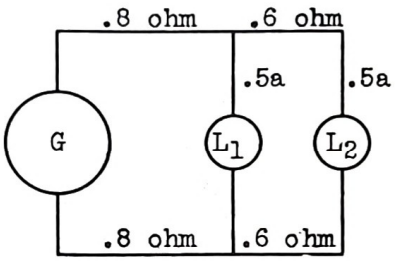


Fig. 14b

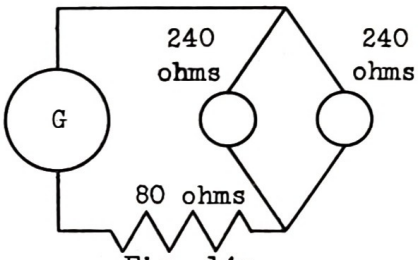


Fig. 14c

4. A resistance of 6 ohms, a parallel combination of two resistances of (D) and 8 ohms, and a parallel combination of three resistances of 10, 16, and 18 ohms are connected in series. What is the resistance of the combination?

5. Three incandescent lamps having resistances of (E), 80, and 76 ohms are connected in parallel. If the total current flowing through them is 8 amperes, determine (a) the voltage across the combination, and (b) the current that flows through each branch.

6. A 550 volt generator supplies 30 amperes to each of two motors. The resistance of each line wire between the generator and the first motor is .4 ohm, and the resistance of each line wire between the first and second motor is (F) ohm. Determine the voltage across each motor.

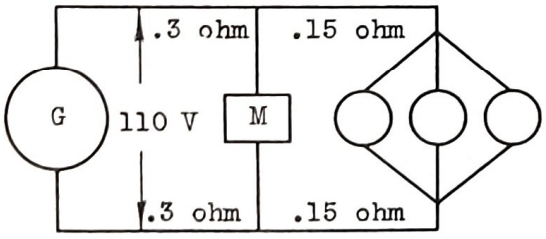


Fig. 14d

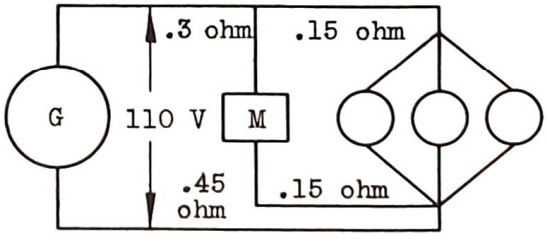


Fig. 14e

7. What must be the voltage at the generator in problem 6 if the voltage across the second motor is to be 550 volts?

8. The motor in the circuit of fig. 14d takes 20 amperes and each lamp takes (G) amperes. The terminal voltage of the generator is 110 volts. Find: (a) the voltage across the motor; (b) across the lamps.

9. If the lamps and motor of problem 8 are connected as shown in fig. 14e, what is the voltage (a) across the motor, and (b) across the lamps?

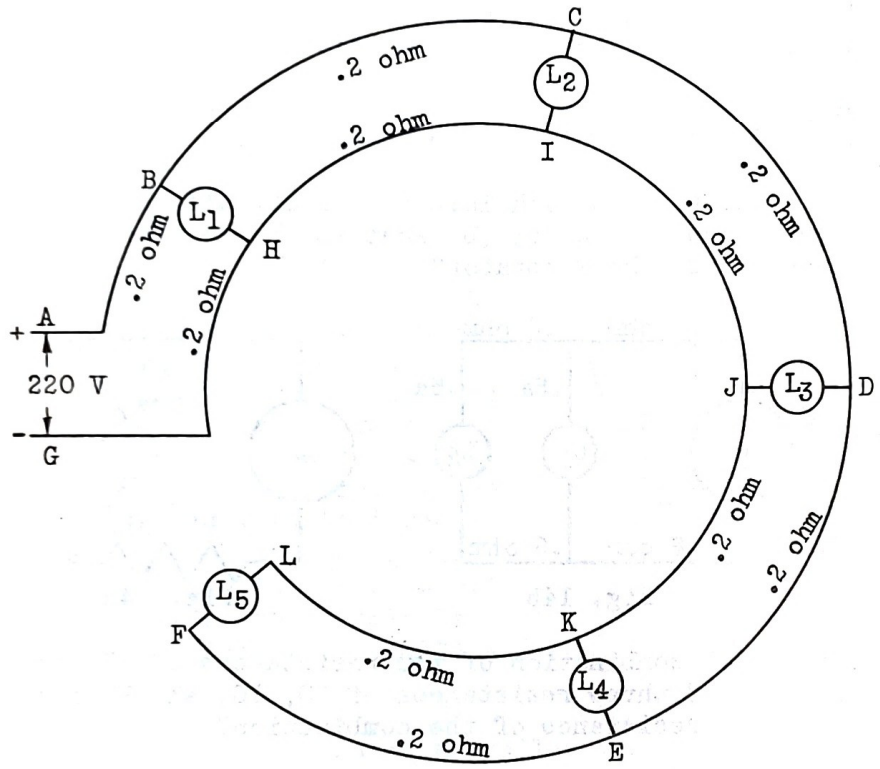


Fig. 15

1. If each lamp in fig. 15 takes (A) ampere, find:
   (a) current flowing in each section of the line;
   (b) voltage in each section;
   (c) voltage across each lamp.

[Tabulate results in form on answer sheet.]

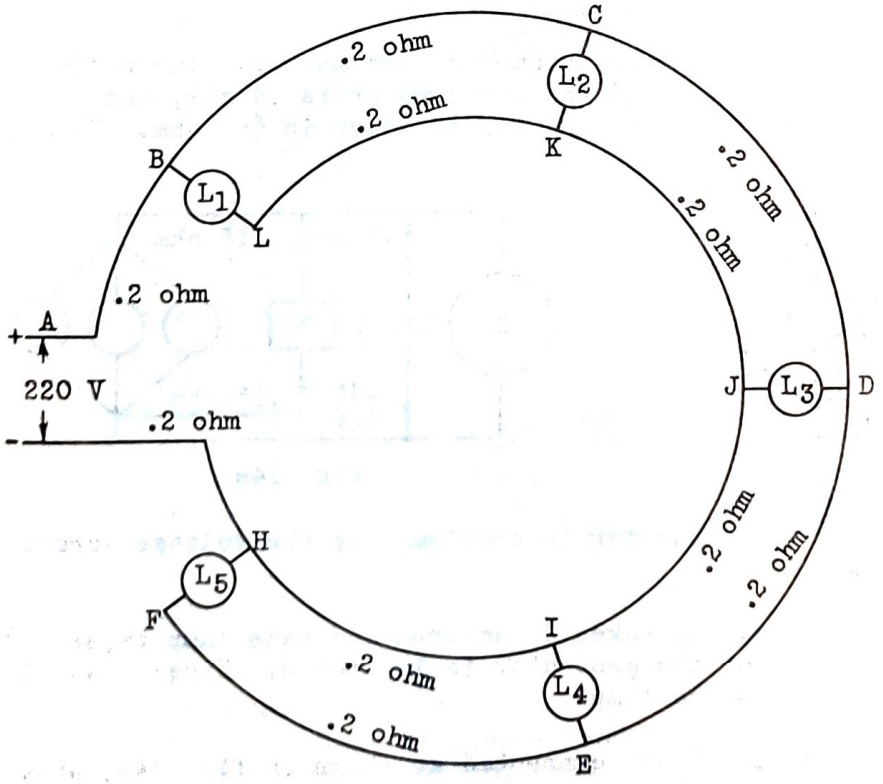


Fig. 16

2. Solve problem 1, assuming that the lamps are connected as shown in fig. 16.

Certain liquids, such as distilled water, alcohol, and kerosene, do not conduct electricity. Other liquids, such as acid and salt solutions, readily conduct electricity. These are known as electrolytes. When current passes through an electrolyte, chemical decomposition takes place. This is known as electrolysis.

ELECTROPLATING.- A very important industrial application of electrolysis is electroplating, which is the process of coating materials with metals by means of an electric current. Suppose it is desired to copper plate a carbon brush. The equipment required is shown in fig. 38. The tank contains a solution of copper sulphate. One molecule of copper sulphate consists of one atom of copper (denoted by Cu), one atom of sulphur (denoted by S), and four atoms of oxygen (denoted by O_4), and is represented by the formula $CuSO_4$. In a solution of copper sulphate, each molecule divides into two parts as shown in fig. 38. Each part is called an ion and has an electric charge. The SO_4 ions each have two extra electrons, making each negatively charged. The two extra electrons on each SO_4 ion come from a Cu ion. Then each Cu ion must have two electrons less than normal and is therefore positively charged. Positive Cu ions migrate to the negative electrode because unlike charges attract, each takes on two electrons to neutralize its charge, and is firmly attached to the brush. The negative SO_4 ions migrate to the positive electrode, each gives off two electrons to neutralize its charge, and combines with one atom of copper to form one molecule of copper sulphate. Then as much copper returns to the solution as is taken from it, and the concentration of the solution does not change. Thus it is possible to continue plating until the copper bar is entirely consumed.

This same method may be used for nickel plating, in which case a solution containing nickel must be used (such as nickel sulphate, $NiSO_4$). The bar suspended from the positive electrode into the solution should also be nickel.

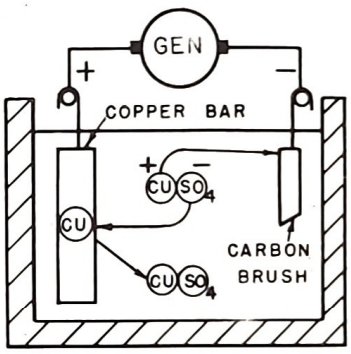


Fig. 38
Copper plating

CELLS.- Chemical energy may be converted into electrical energy by means of cells, each of which generally consists of two plates emerged in an electrolyte. Cells are divided into two kinds--primary cells and secondary cells.

After a primary cell has become run down, its solution must be removed and a new solution supplied. One electrode goes into solution, and must be replaced. A secondary cell differs from a primary cell in that it may be recuperated, after it has run down, by sending a current through it in the opposite direction to that during discharge.

PRIMARY CELL.- Although various combinations of metals and solutions may be used in making a cell, a simple cell may be made by emerging a copper plate and a zinc plate in a diluted solution of sulphuric acid, as shown in fig. 39 (copper is denoted by Cu and zinc by Zn). Each molecule of sulphuric acid consists of two atoms of hydrogen, one atom of sulphur, and four atoms of oxygen, and is represented by the formula H_2SO_4. Each molecule of sulphuric acid breaks up into a negatively charged ion (SO_4) and a positively charged ion (H_2). The SO_4 ions migrate to the Zn electrode, because Zn is more active than H_2, and each unites with one atom of Zn to form $ZnSO_4$, which passes into solution. The zinc plate gains electrons from the SO_4 ions during this action and thus becomes negative.

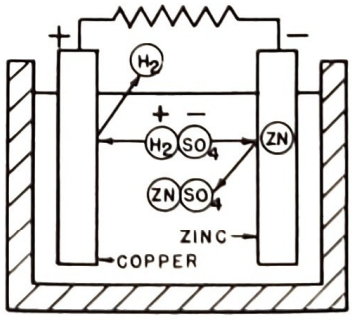


Fig. 39
Simple primary cell

The H_2 ions migrate to the copper, each takes on two electrons, and passes off into the air. This action causes one electrode to become negative and the other positive, and therefore a difference of potential is established between them (about 1.1 volts). When a load is attached to the cell, the chemical action maintains a voltage, which causes electrons to pass through the external circuit from the Zn to the Cu. This action takes place until all the Zn has been converted to $ZnSO_4$ or the sulphuric acid has been consumed.

DRY BATTERY.- The most common type of primary cell is the so-called dry cell, which is shown in fig. 40. The negative electrode is a zinc cup, which is lined with blotting paper. The positive electrode is a carbon rod centrally placed. The space between the blotting paper and the carbon rod contains a paste of sal ammoniac, zinc chloride, manganese dioxide, and ground carbon. This paste is not dry, and if it becomes dry the cell ceases to develop an e m f. The sal ammoniac is the electrolyte, the zinc chloride is added to improve the action, and the manganese dioxide is used to remove the hydrogen bubbles, which otherwise would collect on the carbon electrode and increase the internal resistance of the cell.

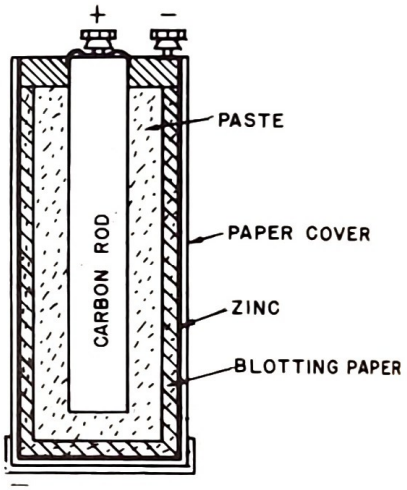


Fig. 40 Section of a typical dry cell

The e m f of a new dry cell is about 1.5 volts and its internal resistance is about .1 ohm. A six inch cell has a capacity of about 32 ampere-hours when discharged through a 20 ohm resistance until the voltage has reduced to .5. Even if a dry cell is not used, its deterioration is such that at room temperature it becomes useless in about one year. If a cell is kept in a cool place, it has a much longer life.

GROUPING OF CELLS.- The number of cells used and the method of grouping them depends upon the voltage and current desired. If cells of equal rating are joined in series (fig. 41a), the total voltage equals the sum of the separate voltages, and the current capacity is the same as that of one cell. If cells of equal rating are connected in parallel (fig. 41b), the total e m f is the same as that of one cell, and the current capacity equals that of one cell times the number of cells. Cells are sometimes arranged as shown in fig. 41c. This is known as a series-parallel arrangement. In this case the total e m f is the same as that of a series group. The current capacity is the same as that of one cell times the number of series groups in parallel.

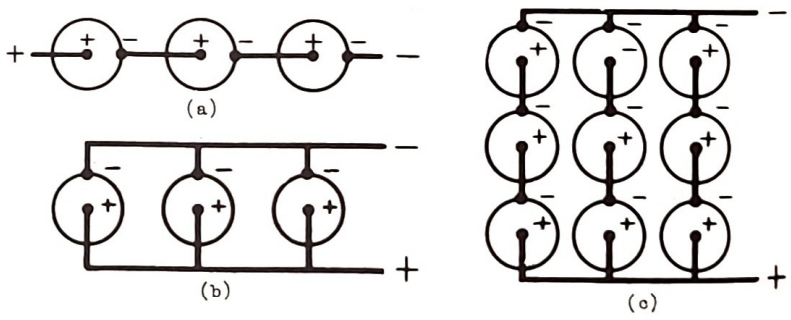


Fig. 41 Methods of connecting batteries

LEAD STORAGE CELL.- In the most common type of storage cell, the negative electrode consists of plates made of spongy lead (denoted by Pb), and the positive electrode consists of plates made of lead peroxide (denoted by PbO_2, which means that each molecule contains one atom of lead and two atoms of oxygen). The electrolyte consists of diluted sulphuric acid. Thin sheets of wood or perforated hard rubber are inserted as insulation between the plates (see fig. 42). If no insulation were used, a short circuit would exist between the plates, causing the battery to discharge internally.

The spongy lead and lead peroxide are relatively poor conductors, and are too soft to be formed into plates. These substances are molded into frames made of some hard material that is a good conductor and does not act as a third electrode, in which case acid would produce action between the frames and the substances molded into them. A frame is generally a casting of an alloy of lead and antimony.

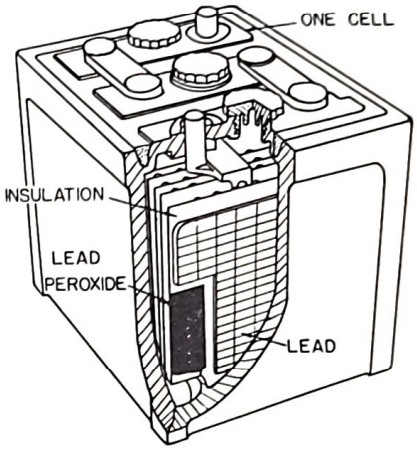


Fig. 42
Cutaway view of a storage cell

CHEMICAL ACTION OF THE LEAD STORAGE CELL DURING DISCHARGE.- Each molecule of sulphuric acid breaks up into a positively charged hydrogen ion (H_2) and a negatively charged sulphate ion (SO_4), as indicated in fig. 43.

Each SO_4 ion near the lead plate combines with one atom in the lead plate to form lead sulphate ($PbSO_4$), and gives up two electrons. Each associated H_2 ion is attracted to the lead peroxide plate, takes on two electrons, and then unites with one atom of oxygen to form a molecule of water (H_2O). This action adds electrons to the lead, making it negative, and removes electrons from the lead peroxide, making it positive. This establishes a difference of potential or voltage.

Each SO_4 ion near the lead peroxide plate combines with a Pb atom in a PbO_2 molecule to form a $PbSO_4$ molecule. Each H_2 ion unites with one atom of oxygen in the PbO_2 molecule to form a molecule of water.

These chemical actions occur simultaneously and may be expressed by the following chemical equation:

$$PbO_2 + Pb + 2H_2SO_4 \rightarrow 2PbSO_4 + 2H_2O$$

This shows that lead sulphate is being formed during discharge. This increases the internal resistance of the cell and the acid becomes weaker. After considerable $PbSO_4$ is formed, the cell becomes too weak for practical use.

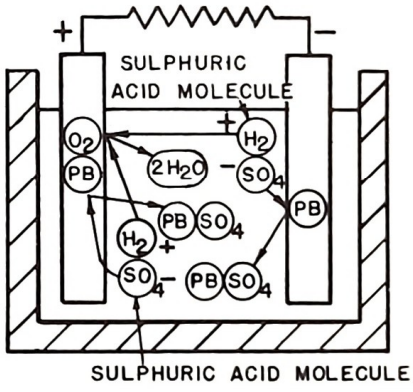


Fig. 43 Chemical action of cell during discharge

CHEMICAL ACTION OF A LEAD STORAGE CELL DURING CHARGE.- The cell may be restored to its former state by sending a current through it in the opposite direction to that during discharge (fig. 44). In this case each molecule of water breaks up into a positively charged hydrogen ion (H_2) and a negatively charged oxygen ion (O). Each H_2 ion is attracted to the negative plate and unites with an SO_4 ion to form a molecule of sulphuric acid, and leaves an atom of spongy lead. Each H_2 ion of other water molecules unites with an SO_4 ion on the positive plate to form a molecule of sulphuric acid. Pairs of liberated O ions combine with each Pb atom in the positive plate to form PbO_2.

Thus, during charge, the water breaks up and combines with the lead sulphate, forming spongy lead at the negative plate and lead peroxide at the positive plate.

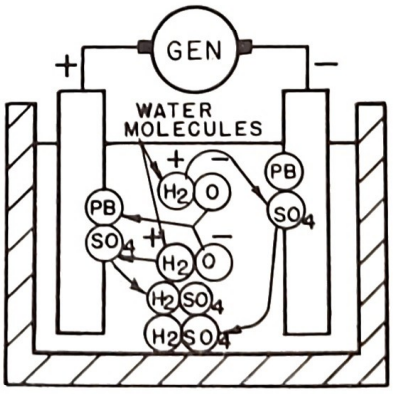


Fig. 44 Chemical action in a cell during charge

This chemical action may be expressed as follows:

$$2PbSO_4 + 2H_2O \rightarrow PbO_2 + Pb + 2H_2SO_4$$

Note, that this chemical action is just the opposite to that which occurs during discharge.

Fig. 45 shows typical charge and discharge curves of a storage cell, in which it will be noted that discharge occurs at nearly a constant e m f of 2 volts.

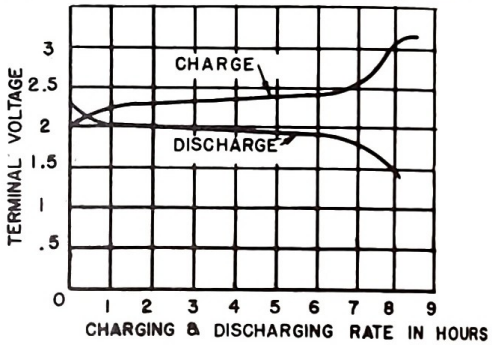


Fig. 45 Voltage variation during charge and discharge

BATTERIES.- A battery usually consists of three cells placed in separate compartments of a single container. These cells are connected in series to obtain maximum voltage (see fig. 42).

RATING OF A BATTERY.- A battery is usually rated according to the maximum current it can supply during an eight hour period, which is known as the normal rate of discharge. A battery that can deliver a maximum of 10 amperes for eight hours is considered an 80 ampere-hour battery.

The ampere-hour capacity of a cell can be estimated by considering that one ampere can be supplied for eight hours for each 25 square inches of surface on the positive plates. In determining the number of square inches in the surfaces, both sides of the positive plates are to be considered.

INTERNAL RESISTANCE.- The internal resistance of a storage battery increases during discharge, due to the formation of lead sulphate, which has a higher resistance than lead or lead peroxide. When charged, a battery has a very low internal resistance (about .00025 ohm). Hence, it may discharge at a very high rate.

CHARGING RATE.- A discharged storage battery can be charged with a high current without overheating. It is permissible to start charging with a current equal numerically to the ampere-hour rating of the battery. For instance, in the case of a discharged 80 ampere-hour battery, charging may be started at 80 amperes. As the battery becomes charged, the rate should be correspondingly decreased. The rate should never be such as to allow violent gassing to take place, because in such a case a considerable amount of the energy supplied to the battery is used in breaking the water up into hydrogen and oxygen and is not effective in charging. Moreover, during gassing the battery becomes heated, which is detrimental because heat causes some of the material to come loose from the plates, thus reducing the amount of active material, damages the separators, and causes buckling of the plates.

Most chargers used in small installations cannot supply the high current mentioned above. These chargers supply a maximum current of about 10 amperes, which is supplied until gassing begins. The current is then reduced to about half value, and is supplied until gassing again begins. The current is decreased repeatedly in this way until charging is completed.

CARE OF A BATTERY.- Water continually vaporizes from a battery, so distilled water must be added occasionally to keep the plates submerged. Undistilled water should not be used, because it may contain impurities which will react with the plates submerged. The acid does not vaporize and none should be added unless some is spilled.

A battery should never be excessively overcharged, especially at a high rate. This causes severe gassing, during which time excessive heat is developed.

The condition of the electrolyte can be determined by a hydrometer (see fig. 46), which has a small glass float with a calibrated stem. This float indicates 1000 when emerged in pure water, 1850 when emerged in pure sulphuric acid, and 1300 when emerged in a battery fully charged.

Whether or not a battery is completely charged cannot always be reliably determined by taking a hydrometer reading, unless the reading at the time of complete discharge is known. If, during the charging period, the hydrometer reading increases 100 above the discharged reading, the battery has undoubtedly become charged.

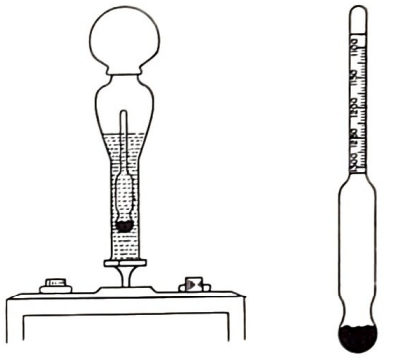


Fig. 46 Typical hydrometer

Another method of determining if a battery is charged is to measure the terminal voltage of each cell, with each discharging at normal rate. If the voltage is two or above, each cell is charged.

The top of a storage battery should be kept free from moisture and dirt, which permit current to leak between electrodes, causing the lugs and supports to corrode. This action is reduced by applying a light coat of grease where corrosion is apt to occur.

SULPHATION.- As previously stated, during discharge both plates change to lead sulphate, which is a very porous material that readily changes back to lead and lead peroxide during charge. If a battery gets too hot, is left discharged for a long time, or has too much sulphuric acid, a deposit of hard sulphate forms on the plates. This sulphate, if excessive, is insoluble and cannot be converted back to lead or lead peroxide. It increases the internal resistance and isolates the active material, decreasing the capacity of the battery.

HYDROMETER READING	FREEZING POINT (°F)
1050	26 above 0
1100	18 " 0
1150	17 below 0
1250	62 " 0
1300	95 " 0

FREEZING.- The temperature at which an electrolyte freezes depends upon the hydrometer reading (see table). This table shows that the freezing point is considerably reduced with an increasing charge on the battery, so that if the battery is well charged there is no danger of it freezing. When the electrolyte in a cell freezes, the plates are usually injured and the case cracks.

HOME WORK

1. What is the difference between a primary cell and a secondary cell?

2. What change in the electrolyte occurs during charge and discharge?

3. Can you determine the charge of a battery by taking a hydrometer reading? Explain.

4. Why should the current be decreased during the charging period?

5. Why is pronounced gassing objectionable in a battery?

6. What is the effect of overcharging?

WORK.- The purpose of every machine is to do a certain amount of work. Some common examples of machines doing work are: a punch press stamping holes in metal, a crane lifting a load of iron, a conveyor moving stock from one place to another, etc. In each of these illustrations it should be noted that a force acts through space. A floor upon which a machine rests does no work because the weight supported is not moved. The amount of work done depends upon the magnitude of the acting force and the distance through which the force acts. Thus

$$\text{Work} = \text{force} \times \text{space} \qquad (1)$$

A common unit of work is known as the foot-pound. A foot-pound of work is done when a force of one pound acts through a distance of one foot.

EXAMPLE.- A man lifts 500 iron rods, each weighing 30 pounds, from the floor to a conveyor 3 feet high. How much work is done?

To place one rod on the conveyor, the work done is 30 × 3 or 90 foot-pounds. The total work done is then 90 × 500 or 45,000 foot-pounds.

POWER.- In the above example observe that the amount of time required to do the work is not considered. The same amount of work is done, regardless of the time used. A weaker man, B for instance, might do the same amount of work as A, provided he had sufficient time. However, A is said to possess greater power because he can do the work in less time. In a given time, a crane can do much more work than either man; consequently, the crane has the greatest power. Thus power differs from work in that time is involved. Power means the rate at which work is done. This may be expressed:

$$\text{Power} = \frac{\text{work}}{\text{time}} \qquad (2)$$

Common units of power are horsepower (H P), watts (W), and kilowatts (kw).

In English-speaking countries the unit "horsepower" is widely used to express the mechanical output of machines. The origin of this unit is briefly as follows:

In early times water was pumped from mines by horses. Later, horses were replaced by steam engines, which were rated as having the power of many horses. The rating of these engines was made possible by James Watt, who determined, by experiment, the number of foot-pounds the average horse used for this purpose could do. He found that for a short time the average horse could work at the rate of 33,000 foot-pounds per minute or 550 foot-pounds per second. This rate was standardized as the "horsepower." Thus,

$$\text{Horsepower} = \frac{\text{foot-pounds per minute}}{33{,}000} \qquad (3)$$

EXAMPLE.- Suppose that in the problem considered above, the man did 45,000 foot-pounds of work in 20 minutes. Find the average horsepower expended.

The work done per minute was 45,000 ÷ 20 or 2250 foot-pounds. The total power was 2250 ÷ 33,000 or .068 horsepower.

WATTS AND KILOWATTS.- It was shown that the flow of electricity through a conductor is similar to the flow of water through a pipe. A flow of water is usually expressed in gallons or pounds per minute; a flow of electricity is usually expressed in coulombs per second, called amperes. The power required to keep water flowing against a certain head is numerically equal to the flow in pounds per minute times the head or pressure in feet. Thus,

$$\text{Power} = \text{pounds per minute} \times \text{feet} \qquad (4)$$

Then to determine the horsepower required to force water against a given head, equation 3 must be expressed as follows:

$$\text{Horsepower} = \frac{\text{pounds per minute} \times \text{feet}}{33{,}000}$$

Similarly, the power required to keep electricity flowing against a certain resistance is numerically equal to the flow in coulombs per second (amperes) times the pressure in volts. This product gives the power in watts. Thus,

$$\text{Watts} = \text{amperes} \times \text{volts}$$

or expressed in algebraic form, $W = IE$ (5)

Thus to determine the power in an appliance, multiply the voltage across the appliance by the current through it.

EXAMPLE.- A heating element takes 20 amperes at 110 volts pressure. What power does it consume?
The power is: $W = 20 \times 110 = 2200$ watts

Since $E = IR$ (Ohm's law), then equation 5 may be expressed as

$$W = I \times IR = I^2R \quad (6)$$

In equation 5, if we substitute for I its value ($I = \frac{E}{R}$), we get

$$W = \frac{E}{R} \times E = \frac{E^2}{R} \quad (7)$$

Equation 6 should be used when the current and resistance are known, while equation 7 should be used when the voltage and resistance are known.

When a large amount of power is considered, a larger unit of power, known as the kilowatt, is used.

$$1 \text{ Kilowatt} = 1000 \text{ Watts}$$

We have now learned that mechanical power is usually expressed in horsepower, and that electrical power is expressed in watts. Since it is often necessary to convert power from one unit to the other, a knowledge of the relation of the two is therefore essential. By experiment it was found that

$$1 \text{ H P} = 746 \text{ watts or } .746 \text{ kilowatt}$$

EFFICIENCY.- Since any electrical appliance has some resistance, heat is produced when a current is sent through it. This heat is wasted unless it is used for heating purposes. Thus no electrical machine converts all the electrical power it receives into mechanical power, or vice versa. The power that a machine receives is called the input, and the power it gives out is called the output. The fraction of the input that is delivered is usually expressed in percentage and is called the efficiency. This may be expressed by an equation, as follows:

$$\text{Input} \times \text{efficiency} = \text{output, or efficiency} = \frac{\text{output}}{\text{input}} \quad (8)$$

In using this equation it should be realized that both the output and input must be expressed in the same unit, that is, either in horsepower, watts, or kilowatts.

EXAMPLE.- A 5 H P motor takes 4.5 k w at full load. Find its efficiency.

$$\text{Output} = 5 \times 746 = 3730 \text{ watts}$$

$$\text{Input} = 4.5 \times 1000 = 4500 \text{ watts}$$

$$\text{Efficiency} = \frac{3730}{4500} = .829 \text{ or } 82.9\%$$

ELECTRICAL UNITS OF WORK.- Equation 2 may be expressed as

$$\text{Work} = \text{power} \times \text{time}$$

This means that the total work done is equal to the rate of doing work (power) times the time. Suppose that a turbine is working at the average rate of 500 horsepower for 24 hours. Then the turbine does 500 × 24 or 12,000 horsepower-hours of work. Similarly, if a generator is supplying electric power at the average rate of 500 kilowatts for 24 hours, the generator supplies 500 × 24 or 12,000 kilowatt-hours of work.

EXAMPLE.- A 200 k w generator runs at full load for 16 hours. How much work is done?

$$200 \times 16 = 3200 \text{ k w h}$$

$$3200 \text{ k w h} = 3200 \div .746 \text{ or } 4290 \text{ h p h}$$

EXAMPLE.- For a two-month period a small consumer is charged 10 cents a k w h for the first 18 k w h, 4 cents a k w h for the next 100 k w h, and $2\frac{1}{2}$ cents a k w h for the remaining consumption. If 150 k w h are used, determine the cost.

For the first 18 k w h the cost is 18 × .10 or $1.80.

For the next 100 k w h the cost is 100 × .04 or $4.00

For the remaining k w h (150 - 100 - 18 = 32) it will cost 32 × .025 = $.80

The total cost is then $1.80 + $4.00 + $.80 = $6.60

MEASUREMENT OF HEAT.- Before we can understand how the heating effect of electricity is determined, we must become familiar with the unit in which heat is measured. This unit is called the British Thermal Unit (abbreviated to B T U), and its size has been established as follows:

<u>A British Thermal Unit is the amount of heat necessary to raise one pound of water one degree Fahrenheit</u>.

When it is desired to find the amount of heat necessary to raise a quantity of water to a certain temperature from an initial temperature, it is only necessary to multiply the weight of the water by the temperature rise in degrees Fahrenheit.

Expressing this by an equation,

$$H = Qt \qquad (8a)$$

where H = the amount of heat in B T U, Q = quantity of water in pounds, and t = the change in temperature in degrees Fahrenheit.

EXAMPLE.- How many B T U of heat are required to raise one gallon of water (8-1/3 lbs) from 75° F to the boiling point (212° F)?
Substituting in the above equation,

$$H = 8\tfrac{1}{3}(212 - 75) = 1141.66 \text{ B T U}$$

HEATING EFFECT OF AN ELECTRIC CURRENT.- A convenient method of measuring the amount of heat produced by an electric current passing through a resistance is by means of a calorimeter (fig. 1). This is simply a vessel containing water, in which a thermometer and a one-ohm resistance are placed. The vessel is usually surrounded by a material which is a poor conductor of heat, so that the heat generated will not be carried away by the surrounding air. The number of B T U developed in the wire may be determined by Equation 8a. It has been found that when one ampere flows through a one-ohm resistance for one minute, .057 B T U of heat will be generated. Hence, it produces .057 B T U per minute.
From this we conclude that the amount of heat produced per minute by current passing through a resistance R is .057 I^2R. The heat produced for any length of time is .057 I^2R multiplied by the time in minutes (t). This may be expressed as

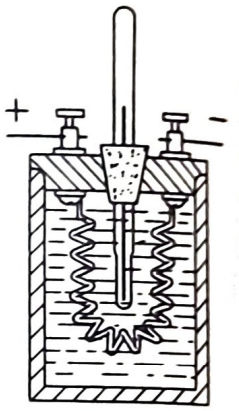


Fig. 1
Calorimeter

$$H = .057\ I^2Rt \qquad (8b)$$

EXAMPLE.- How many B T U are generated in one hour by a heating element which carries 20 amperes and has 2 ohms resistance?

$$H = .057 \times 20^2 \times 2 \times 60 = 2736 \text{ B T U}$$

HOME WORK

1. In two minutes a man raises a 50 pound weight to a distance of A feet. Determine (a) the amount of work done, and (b) horsepower of the man while raising the weigh
2. Compute the number of watts supplied to a 20 ohm electric heater when B amperes are flowing through it.
3. What full load current will a C volt, 15 horsepower generator deliver?
4. Express D watts in kilowatts. In horsepower.
5. At its rated load a motor is 80 per cent efficient and takes 50 amperes at E volts. What is its horsepower output?
6. Determine the number of B T U necessary to raise the temperature of F pounds of water 50° F.
7. Find the number of B T U generated by a current of G amperes flowing through a 50 ohm resistance for five minutes.

Expressing this by an equation,

$$H = Qt \qquad (8a)$$

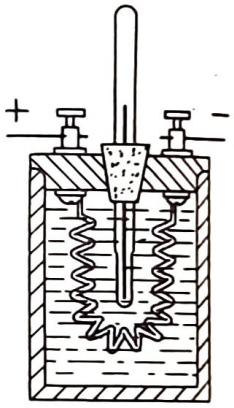
where H = the amount of heat in B T U, Q = quantity of water in pounds, and t = the change in temperature in degrees Fahrenheit.

EXAMPLE.- How many B T U of heat are required to raise one gallon of water (8-1/3 lbs) from 75° F to the boiling point (212° F)?
Substituting in the above equation,

$$H = 8\tfrac{1}{3}(212 - 75) = 1141.66 \text{ B T U}$$

HEATING EFFECT OF AN ELECTRIC CURRENT.- A convenient method of measuring the amount of heat produced by an electric current passing through a resistance is by means of a calorimeter (fig. 1). This is simply a vessel containing water, in which a thermometer and a one-ohm resistance are placed. The vessel is usually surrounded by a material which is a poor conductor of heat, so that the heat generated will not be carried away by the surrounding air. The number of B T U developed in the wire may be determined by Equation 8a. It has been found that when one ampere flows through a one-ohm resistance for one minute, .057 B T U of heat will be generated. Hence, one watt produces .057 B T U per minute.

From this we conclude that the amount of heat produced per minute by a current passing through a resistance R is .057 I^2R. The total heat produced for any length of time is .057 I^2R multiplied by the time in minutes (t). This may be expressed as



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Electric motors are used so extensively for supplying mechanical power because they are easily controlled and have a relatively high efficiency. The efficiency of a motor is found by dividing the output by the input, as stated in Lesson 9. The input in watts is found by multiplying the line voltage by the supplied current, the voltage and current being measured by instruments.

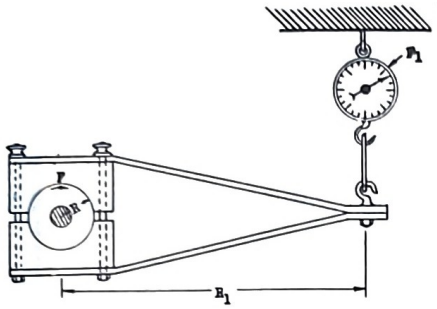


Fig. 1 Typical prony brake for measuring output of motor

The output of small and medium size motors may be determined by means of a prony brake, a common form of which is shown in fig. 1. It consists of two blocks of wood shaped to fit round the pulley of the motor. The pressure of these blocks against the pulley may be varied by means of the two hand wheels at the top. The two bars fastened at the top and bottom of the brake form an arm which is attached to a scale. When the armature turns, the friction between pulley and wooden blocks converts the power supplied by the motor into heat.

In developing an equation for the horsepower converted into heat, let R represent the radius of the pulley in feet, and F the force supplied at the surface of the pulley. Then when the pulley completes one revolution, the force F moves a distance of $2\pi R$ feet, and therefore $F(2\pi R)$ foot-pounds of work is done. If the pulley rotates at the rate of N revolutions per minute, $2\pi FRN$ foot-pounds of work is done. Since one horsepower is developed for every 33,000 foot-pounds of work done per minute, then to convert foot-pounds per minute into horsepower, we must divide by 33,000. Hence,

$$H\,P = \frac{2\pi FRN}{33000}$$

$$\text{or} \qquad H\,P = \frac{FRN}{5252} \tag{9}$$

TORQUE.- The twisting effect produced by a motor does not depend only upon the magnitude of the force F, but also upon the radial distance this force acts. The twisting effect is expressed as the product of the force F and the radius R through which the force acts, and is called torque. Torque is represented by T and is expressed in pound-feet, as

$$T = FR \tag{10}$$

Then Equation 9 may be expressed as

$$H\,P = \frac{TN}{5252} \tag{11}$$

EXAMPLE.- A motor rated at 12 horsepower runs at 850 r p m. What twisting effect (torque) will the motor supply at its rated load?

From Equation 10,

$$T = \frac{5252\ H\ P}{N} = \frac{5252 \times 12}{850} = 74.146 \text{ pound-feet}$$

In the case of the brake shown in fig. 1, it should be realized that the product of scale reading F_1 (see fig. 1) and the length of arm R_1 gives a torque which opposes the torque produced by the motor and is equal to it. Since, in practice, the scale reading F_1 and the arm length R_1 are easily obtained, the torque delivered by the motor may be determined by taking the product of these values. That is,

$$T = F_1R_1 \tag{12}$$

The horsepower output is then found by substituting in Equation 11.

EXAMPLE.- A prony brake attached to a motor as shown in fig. 1 has an arm 10.5 inches long. The scale indicates 15 pounds when the pulley revolves at 1800 r p m. Determine the output of the motor at this particular load.

From equation 12, $T = 15 \times \frac{10.5}{12} = 13.125$ pound-feet

From equation 11, $H\,P = \frac{13.125 \times 1800}{5252} = 4.498$ or 4.5 horsepower

EXAMPLE.- Find the efficiency of the motor in the above example if it takes 18 amperes at a pressure of 240 volts.

The output of the motor is 4.5 horsepower or 3357 watts. The input is 18 × 240 or 4320 watts. The efficiency is then

$$\frac{3357}{4320} = .777 \text{ or } 77.7\%$$

TRANSMISSION OF POWER.- Machines may be divided into two classes--the driving machine, which usually consists of some type of electric motor, and the driven machine, such as a press, a lathe, a planer, or a grinder.

The usual connecting links between the driving and the driven machine are belts on pulleys (or chains on gears), direct gear drives, or shafts.

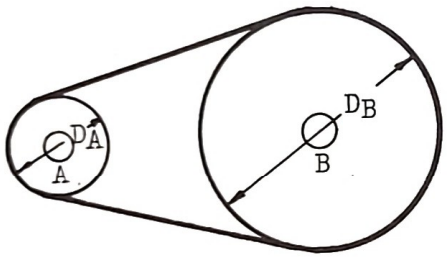


Fig. 2 Transmission of power with a belt

When two pulleys are connected by a belt (fig. 2), their surface speeds are the same. Letting D represent the diameter and N represent the revolutions per minute, the surface speed of A is $\pi D_A N_A$, and the surface speed of B is $\pi D_B N_B$. It follows that $\pi D_A N_A = \pi D_B N_B$, or

$$\frac{N_A}{N_B} = \frac{D_B}{D_A} \qquad (13)$$

This equation shows that the speed of these pulleys is inversely proportional to their diameters. For instance, if B has twice the diameter of A, it will run one-half as fast.

EXAMPLE.- Fig. 3 shows a 10 H P motor supplying power to a machine by means of a belt drive. If the motor runs at 900 r p m, determine the speed, torque, and horsepower that the driven pulley supplies to the load.

The speed of B is

$$N_B = \frac{N_A D_A}{D_B} = \frac{900 \times 8}{20} = 360 \text{ r p m}$$

The surface force on the two pulleys is the same. Hence for A (or B),

$$F = \frac{5252\ H\ P}{RN} = \frac{5252 \times 10}{300} = 175.06 \text{ pounds}$$

Then the torque supplied by B is

$$\frac{10}{12} \times 175.06 = 145.88 \text{ pound-feet}$$

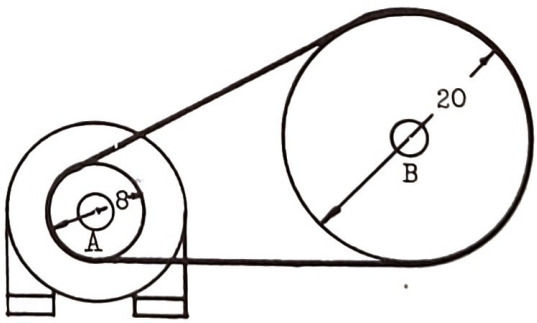


Fig. 3 Motor supplying power to a load by means of a belt drive

If friction is neglected, the horsepower delivered by B is the same as that delivered by A, because the product RN in Equation 9 will be the same in either case.

Equation 13, which gives the relative speeds of two pulleys connected by a belt, also applies to two gears in mesh (fig. 4). However, in this case we realize that the teeth ratio is proportional to the diameter ratio. Letting T represent the number of teeth, then

$$\frac{N_A}{N_B} = \frac{T_B}{T_A} \qquad (14)$$

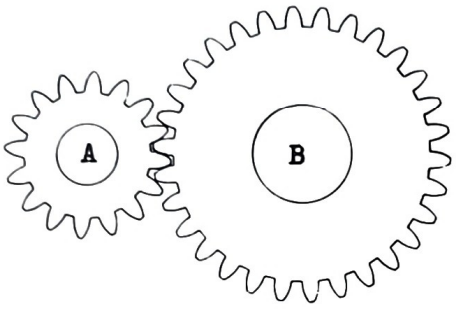


Fig. 4
Transmission of power by gears

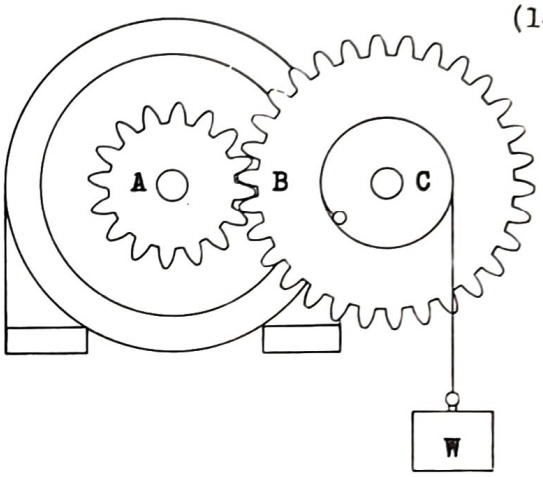


Fig. 5 One method of using a small motor to raise a large weight

SHAFTS.- When two pulleys, two gears, or a pulley and a gear, are connected by means of a shaft, the twisting effect of the two are always equal. The following example is given to show how a problem involving at least one of these conditions is solved.

EXAMPLE.- Fig. 5 shows a 5 H P motor running at 1200 r p m. On its shaft is a 4 inch gear in mesh with a 24 inch gear. The second gear is attached to shaft C, which is 6 inches in diameter. What maximum weight W can a rope winding on this shaft raise?

From Equation 9 the force on the surface of A is

$$F = \frac{5252 \text{ H P}}{RN} = \frac{5252 \times 5}{\frac{2}{12} \times 1200} = 131.3 \text{ pounds}$$

Since the force acting on B is also 131.3 pounds, the twisting effect of B is

$$T_B = \frac{12}{12} \times 131.3 = 131.3 \text{ pound-feet}$$

The torque due to the weight W at the end of the rope will be equal and opposite that of pulley B; hence, the force F on the surface of shaft C becomes

$$131.3 \div \frac{3}{12} = 525.2 \text{ pounds}$$

Thus with this combination the 5 H P motor will raise 525.2 pounds at its rated load.

1. Find the force F that must be exerted on the handle of the windlass in fig. 6 in order to raise the weight.

2. A certain motor at full load supplies 12 horsepower to a prony brake and takes B amperes at a pressure of 240 volts. Determine its efficiency at full load.

3. Suppose that the prony brake shown in fig. 1 is attached to a motor to be tested and that the arm of the brake is 18 inches long. If the motor runs at 1200 r p m and the scale indicates C pounds, what horsepower is delivered?

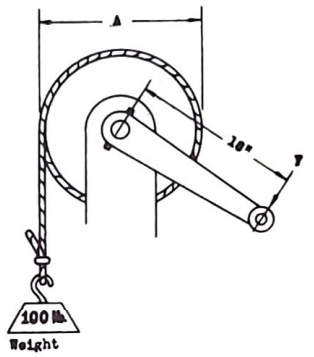


Fig. 6

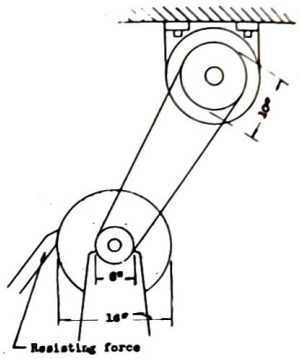


Fig. 7

4. What torque does the motor in problem 3 supply?

5. In fig. 7 determine the horsepower and speed of the motor driving the grinding wheel, if this wheel rotates at 2000 r p m and has a surface resisting force of D pounds.

6. Pumps in the power house of the Ford Motor Company raise 8,300,000,000 pounds of water 2 feet in 24 hours. Compute the horsepower of the electric motors used to drive these pumps if they are E per cent efficient.

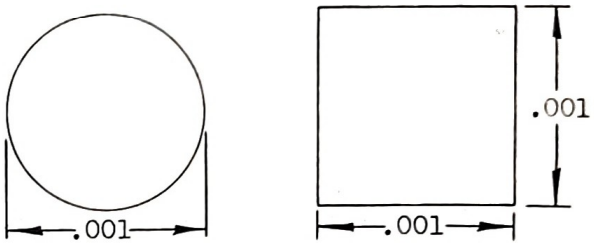
7. A 12 inch pulley on a motor shaft is belted to a 20 inch pulley. If the torque supplied to the 12 inch pulley is F pound-feet, what is the torque delivered by the 20 inch pulley?

8. A G inch pulley on the shaft of a 10 horsepower motor drives by belt a 24 inch pulley at 480 r p m. Determine the torque supplied by the motor at full load.

9. A 40 tooth gear on a 5 horsepower motor drives an H tooth gear at 2000 r p m. At full load what torque is supplied by the motor?

10. A J inch pulley on the shaft of a 12 horsepower motor drives by belt a 30 inch pulley on a second shaft at 1800 r p m. What horsepower motor running at 1200 r p m with an attached pulley must be used to raise the speed of the second shaft to 2400 r p m and supply the same torque?

CIRCULAR MILS.- Due to the fact that a wire generally has a very small diameter, it is convenient to express its thickness in thousandths of an inch. One thousandth of an inch is therefore the unit of measure and is called a mil. Instead of saying that a certain wire has a diameter of .032 inch, it is said to have a diameter of 32 mils. The area of a circular conductor is expressed in terms of a unit of area called the circular mil (fig. 8a), which is the area of a circle that has a diameter of one mil. The diameter in mils is denoted by m and the area in circular mils by (m).



(a) Circular mil (b) Square mil

Fig. 8
Comparison of circular and square mil

The area of a circular conductor is expressed in circular mils because there is a very simple relation between mils and circular mils. This relation may be developed in the following way.

Let A equal the area of a circle expressed in square inches and D equal the diameter in inches. Then

$$A = .7854D^2 \tag{15}$$

The area of one circular mil is therefore $.7854 \times .001^2 = .0000007854$ square inch. There are as many circular mils in a conductor as the area of one circular mil is contained in the area (A) of the conductor. Therefore,

$$(m) = \frac{A}{.0000007854} = \frac{.7854D^2}{.0000007854} \tag{16}$$

But $D = \frac{m}{1000}$, and therefore $D^2 = \frac{m^2}{1,000,000}$ (17)

Substituting equation 17 into equation 16, $(m) = \frac{.7854 \times \frac{m^2}{1,000,000}}{.0000007854} = m^2$ (18)

Therefore, $(m) = m^2$ (19)

Equation 19 may be expressed as follows: To find the number of circular mils in a conductor, square the diameter expressed in mils.

EXAMPLE.- Find the number of circular mils in a conductor .025 inch in diameter.

.025 inch = 25 mils

Then, $(m) = 25^2 = 625$ circular mils

Instead of determining the area of a conductor in square inches, it is easier to determine it in circular mils because the value .7854 is not involved. Also, the answer is a whole number.

EXAMPLE.- What is the diameter of a wire in inches if it has an area of 5184 circular mils?

$$m = \sqrt{(m)} = \sqrt{5184} = 72 \text{ mils or } .072 \text{ inch}$$

MIL-FOOT WIRE.- A wire one mil in diameter and one foot long is considered a mil-foot wire (fig. 9). One foot of any wire may be considered to be composed of a number of mil-foot wires in parallel. The resistance of any number of similar wires in parallel is equal to the resistance of one of them divided by the total number. It has been found experimentally that the resistance of a hard drawn copper wire one mil in diameter and one foot long is 10.4 ohms. The resistance of a wire of the same material and length but 10 circular mils in cross section is 10.4 ÷ 10 or 1.04 ohms. The resistance of a wire varies directly with its length. If the 10 circular mil copper wire is 1000 feet long, its resistance is 1.04 × 1000 or 1040 ohms.

To find the resistance (R) of any wire, then, it is merely necessary to divide the resistance of one mil-foot of the wire (K) by the cross section in circular mils (Ⓜ) and multiply by the length (l). The same idea is conveyed by the following equation.

$$R = \frac{Kl}{Ⓜ} \qquad (20)$$

EXAMPLE.- Find the resistance of a copper wire .15 inch in diameter and one mile long.

A copper wire .15 inch in diameter contains 22,500 circular mils. Then

$$R = \frac{10.4 \times 5280}{22,500} = 2.44 \text{ ohms}$$

SQUARE MILS.- Areas of rectangular conductors, such as bus bars, are more conveniently expressed in terms of a unit of area called the square mil. One square mil is the area of a square with sides one mil in length (fig. 8b), and is denoted by the symbol [m]. The number of square mils in a rectangular conductor may be determined by multiplying together the thickness and width expressed in mils.

EXAMPLE.- Find the area in square mils of a bus bar 1/4 inch thick and 2 inches wide.

1/4 inch equals 250 mils and 2 inches equals 2000 mils. Then the area is 250 × 2000 or 500,000 square mils.

The area of a rectangular conductor in square mils may also be found by multiplying its area (A) in square inches by 1,000,000. That is,

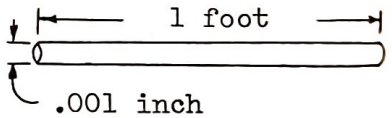


Fig. 9
Circular mil-foot wire

$$[m] = 1,000,000A \qquad (21)$$

EXAMPLE.- How many square mils are contained in a conductor .75 square inch in cross section?

$$[m] = 1,000,000 \times .75 = 750,000 \text{ square mils}$$

There are as many circular mils in a rectangular conductor as the area of one circular mil is contained in the area (A) of the conductor. Then the number of circular mils is

$$Ⓜ = \frac{A}{.0000007854} \qquad (22)$$

According to equation 21, however, $A = \frac{[m]}{1,000,000}$

Substituting $\frac{\boxed{m}}{1,000,000}$ for A in equation 22, then, we have

$$\textcircled{m} = \frac{\frac{\boxed{m}}{1,000,000}}{.0000007854} = \frac{\boxed{m}}{.7854}$$

Therefore, $$\textcircled{m} = \frac{\boxed{m}}{.7854} \qquad (23)$$

Therefore, to find the number of circular mils in a rectangular conductor, divide the area expressed in square mils by .7854.

EXAMPLE.- Find the number of circular mils in a conductor 1/8 by 1 inch. 1/8 inch = 125 mils and 1 inch = 1000 mils. Then the area is 125 × 1000 or 125,000 square mils. Substituting in equation 9,

$$\textcircled{m} = \frac{125,000}{.7854} = 159,154 \text{ circular mils}$$

The resistance of a rectangular conductor may be computed by first finding its area in square mils, reducing this to circular mils, and then substituting in equation 20.

RESISTIVITY.- Table I gives the resistance per mil-foot, called the resistivity, of the materials most commonly used as conductors. It will be seen that silver has the lowest resistivity. While this metal has excellent properties, it is not used to any great extent because of its high cost.

Nearly all electric conductors are made of copper because this material is nearly as good a conductor as silver, will bend easily without breaking, is strong, is inexpensive, and can be soldered easily.

B & S Gage No.	Diameter in Mils	Area in Circular Mils	Ohms per 1000 ft. at 20° C	B & S Gage No.	Diameter in Mils	Area in Circular Mils	Ohms per 1000 ft. at 20° C
000	409.6	167772	.062	20	32.0	1024	10.15
00	364.8	133079	.078	21	28.5	812	12.80
0	324.9	105560	.098	22	25.3	640	16.14
1	289.3	83694	.124	23	22.6	511	20.36
2	257.6	66358	.156	24	20.1	404	25.67
3	229.4	52624	.197	25	17.9	320	32.37
4	204.3	41738	.248	26	15.9	253	40.81
5	181.9	33088	.313	27	14.2	202	51.47
6	162.0	26244	.395	28	12.6	159	64.91
7	144.3	20822	.498	29	11.3	128	81.80
8	128.5	16512	.628	30	10.0	100	103.2
9	114.4	13087	.792	31	8.9	79	131.0
10	101.9	10384	.999	32	7.9	62	164.8
11	90.7	8226	1.260	33	7.1	50	207.0
12	80.8	6529	1.588	34	6.3	40	260.0
13	71.9	5170	2.003	35	5.6	31	329.0
14	64.1	4109	2.521	36	5.0	25	414.8
15	57.1	3260	3.184	37	4.5	20	522.3
16	50.8	2581	4.016	38	4.0	16	659.0
17	45.3	2052	5.064	39	3.5	12	835.0
18	40.3	1624	6.385	40	3.1	10	1040.0
19	35.9	1289	8.051	-	-	-	-

TABLE I

The resistivity of aluminum is about 1.6 times as great as copper, but due to the fact that aluminum is only 30 per cent as heavy, it has less resistance per pound than copper, for a given length. For equal resistance per foot, aluminum has a greater cross section than copper, and this limits its use with an insulating cover and inclosure. Aluminum has less strength and melts at a lower temperature than copper, and is not readily soldered. It is used to some extent for bus bars, because the large cross section which is required provides more radiating surface than copper would give.

All other materials given in Table I have a much higher resistivity than copper. These materials are generally used in circuits in which resistance is desired to restrict the flow of current or produce heat.

WIRE GAGES.- Wires are manufactured in sizes numbered according to what was formerly known as the Brown & Sharpe (B & S) gage but is now known as the American wire gage (A W G). The numbering of these gages is given in Table II. It will be seen that the numbers are in reverse order, that is, the large numbers denote a small size of wire. For every third gage of smaller size, the wire halves in cross section and therefore doubles in resistance. Therefore, the ratio of cross sections between any two sizes must be $\sqrt[3]{2}$ or 1.26 to 1. Furthermore, a No. 10 wire is practically 1/10 of an inch in diameter, has a cross section of 10,000 circular mils, and has a resistance of about one ohm per 1000 feet. With these facts in mind, it is possible to estimate quickly the area and resistance of any size of wire and any length, without using the table.

MATERIALS	RESISTIVITY (K) AT 20° C	TEMPERATURE COEFFICIENT PER DEGREE C*
Aluminum	17.7	0.0043
Carbon	-	-0.0005
Constantan	296	-
Copper	10.4	0.0043
German Silver Wire	200	0.0004
Iron Wire	60	0.006
Iron (cast)	500	-
Manganin	266	0.00002
Nichrome	610	0.0004
Nickel	60	0.006
Silver	9.5	0.004
Steel (soft)	90	0.0044
Steel (hard)	275	0.0016
Tungsten (annealed)	26	0.005
Tungsten (hard drawn)	33	0.005

*Average of values between 0° and 100° centigrade.

TABLE II

For example, to estimate the cross section and resistance per 1000 feet of No. 17 wire, count from No. 10 to No. 16 by threes. This requires two steps, indicating an area one-fourth that of No. 10, or 2500 circular mils, and a resistance of four times that of No. 10, or 4 ohms. Since the ratio of one size to the next is 1.26, the area of No. 17 is 2500 ÷ 1.26 = 1984 circular mils, and its resistance is 4 × 1.26 or 5.04 ohms.

HOME WORK

1. How many mils are there in .339 of an inch?
2. How many circular mils are contained in a wire 461 mils in diameter?
3. Find the number of circular mils in a conductor .182 of an inch in diameter.
4. What is the diameter of a conductor in inches that has a cross-sectional area of 243,049 circular mils?
5. Find the number of square mils in a rectangular conductor that is .675 of an inch thick and one inch wide.
6. How many circular mils are contained in a bus-bar 3/8 by 1.75 inches?
7. Calculate, in inches, the diameter of a circular conductor that will have the same area as a bus-bar 1/4 by 3 inches.
8. If a rectangular conductor is to be used instead of a cable containing 105,530 circular mils, what will be its cross-sectional area in square inches?
9. A cable is composed of 16 strands of wire and each strand is .144 of an inch in diameter. Find the area of the cable in circular mils.
10. Determine the resistance of one mile of aluminum wire .25 inch in diameter.
11. What length of nichrome wire, 1000 circular mils in cross section, is required to give a resistance of 5 ohms?
12. What size iron wire will have the same resistance as a No. 18 copper wire of the same length?

CURRENT CARRYING CAPACITY OF CONDUCTORS.- When current passes through a conductor, heat is generated and its temperature rises. This rise continues until a temperature is reached at which the air carries away the heat as fast as it is produced (the rate at which heat is carried away is proportional to the temperature difference between the wire and the surrounding air). If the current is high, the temperature reached may be high enough to damage the insulation. For power wiring, where the current may flow for long periods, it should not exceed the values given in Table III, which were taken from the National Electric Code. For aluminum wire, the current should not exceed 84 per cent of the values given.

SIZE OF CONDUCTOR	CURRENT CARRYING CAPACITY IN AMPERES		
	RUBBER INSULATION	VARNISHED CAMBRIC INSULATION	OTHER INSULATION
18	3		6
16	6		10
14	15	18	20
12	20	25	30
10	25	30	35
8	35	40	50
6	50	60	70
5	55	65	80
4	70	85	90
3	80	95	100
2	90	110	125
1	100	120	150
0	125	150	200
00	150	180	225
000	175	210	275
0000	225	270	325

TABLE III

In selecting wire sizes, it is essential that the wire be large enough to carry the current without overheating and also large enough to keep a low voltage drop in the line. For feeders supplying power to lamps, the voltage drop should not exceed 3 per cent of that impressed on the input end, because even a low voltage drop causes an appreciable reduction in the efficiency of the lamps. For example, a voltage drop of 10 per cent causes the lamps to supply 30 per cent less light, while the power consumed is reduced only 19 per cent.

If the load consists of motors or heating units, a drop of 10 per cent is not objectionable.

EXAMPLE.- What size wire is required for transmitting 10 amperes from a 120 volt generator to a bank of lamps 875 feet away if the line drop is not to exceed 3 per cent of the generated voltage?

The permissible line drop is .03 × 120 or 3.6 volts, and the line resistance must be 3.6 ÷ 10 or .36 ohm.

The length of the line is 2 × 875 or 1750 feet.

The resistance per 1000 feet of wire, then, is .36 ÷ 1.75 or .206 ohm. The wire size nearest this resistance is No. 3 (see Table I). According to Table III, this gage is large enough to carry the current without overheating.

WIRING SYSTEMS.- Lamps of 120 volts rating are the most common because they are durable and economical. Lamps with a higher rating have a longer and thinner filament, which is more apt to break or burn out, and lamps with a lower rating require a lower voltage supply line. Such a line will have greater copper losses unless larger line wires are used (a more costly installation). A common method of reducing line losses and the amount of copper required for transmission will now be considered.

PROBLEM 1.- Determine the line loss when eight 120 volt, 60 watt lamps are connected at the end of a 4 ohm line which supplies 120 volts.

Each lamp takes 60 ÷ 120 or .5 amp, and the line current is .5 × 8 or 4 amps (see fig. 10). The loss in the line wires is therefore 4^2 × 4 or 64 watts.

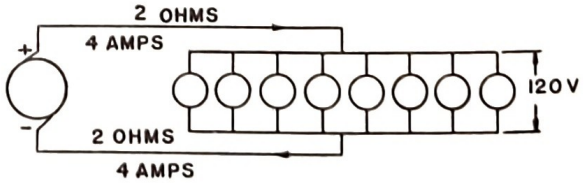


Fig. 10
Power line with a lighting load

PROBLEM 2.- Solve problem 1 if 240 volts are supplied to the lamps paired off in series as shown in fig. 11.

In this case the line current is 2 amperes and the line loss is $2^2 \times 4$ or 16 watts, one-fourth the loss of problem 1. This is due to the fact that the line loss varies as the square of the current. For a given power line, then, when the voltage is doubled, the line loss becomes one-fourth as much, or for the same line loss the line resistance is four times as much as that obtained by using wires of one-fourth the cross section. This suggests the following rule: When the voltage of a power line is doubled, one-fourth as much copper is required for the same line loss.

The decrease in power loss, obtained merely by doubling the voltage, suggests connecting 120 volt lamps to a 240 volt line as shown in fig. 11. With this system, however, two lamps must be used when only one is needed, four when three are needed, etc. To eliminate this undesirable feature and still supply power to 120 volt lamps at 240 volts, a third wire called the neutral is added to a 240 volt line such as the one shown in fig. 11, forming a circuit known as a three wire system. The National Electric Code requests that this neutral wire be of the same size as each of the other two, which is necessary when the lights on only one side of the system are turned on.

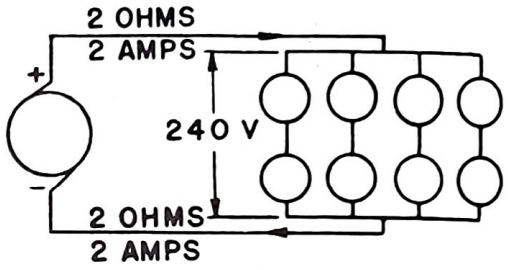


Fig. 11 Method of connecting lamps to reduce the line losses

It was shown above that a 240 volt, two wire system requires one-fourth the copper of a 120 volt system. By employing a neutral wire the same size as each of the others (see fig. 12), the amount of copper required is 1/4 + 1/8 or 3/8 of that required in a 120 volt system.

In a three wire system, a small unit called a balancer set is generally used, to which the neutral is attached. In dealing with lighting loads, however, it is more convenient to consider the power as being supplied from two generators in series, as shown in fig. 13.

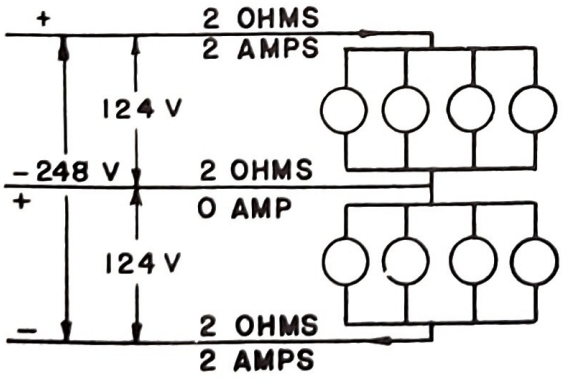


Fig. 12
Balanced three wire system

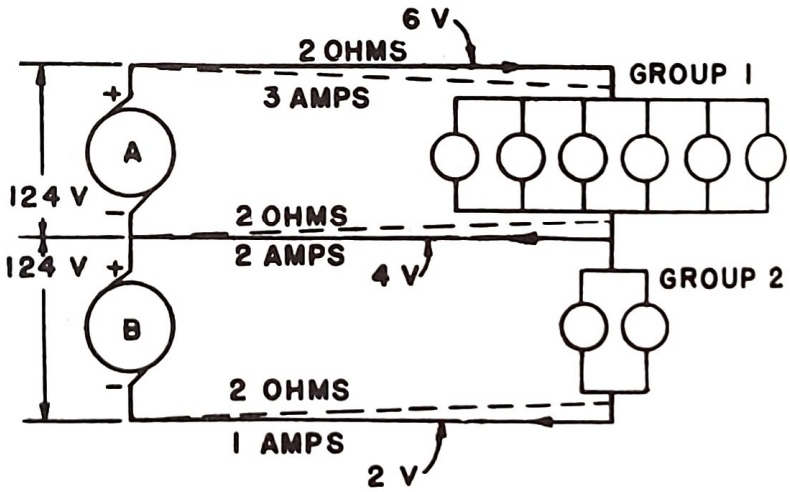


Fig. 13
Unbalanced three wire system

THREE WIRE SYSTEMS.- When the lamps on each side of the neutral take the same amount of current, as in fig. 12, the neutral carries no current and the system is said to be balanced. When the lamps on one side take a different amount of current to those on the other side, the system is said to be unbalanced. In fig. 13, the lamps on one side of the neutral take 3 amps and those on the other side take 1 amp.

The neutral must carry the difference of the currents in the two outer wires, or 2 amps. In practice, an effort is made to keep the system balanced because in such a system the current and voltage distributions are the same as in the 240 volt, two wire system with lamps connected series parallel. A balanced condition seldom exists, however, because more lamps are usually turned on on one side of the neutral than on the other. In an unbalanced system, the voltage at the load, between the neutral and the + wire, is not the same as that between the neutral and the - wire.

EXAMPLE.- Determine the voltages across group 1 and group 2 in fig. 13.

The voltage drop for each line wire is indicated graphically by dotted lines. The fall of potential, which, in a line wire, always occurs in the direction in which the current flows, is indicated by a downward slope. In determining the voltage across group 1, the dotted lines indicate that the voltage drop in the positive line and in the neutral line must be subtracted from the voltage of generator A, which gives 124 - 6 - 4 = 114 volts. In determining the voltage across group 2, the dotted lines indicate that the voltage drop in the neutral must be added to the voltage of generator B, while the voltage drop in the negative wire must be subtracted, giving 124 + 4 - 2 = 126 volts. Since the lamps are all rated at 120 volts, the voltage across group 1 is too low and the voltage across group 2 is too high.

OPEN NEUTRAL IN A THREE WIRE SYSTEM.- If the neutral in an unbalanced system becomes open, current and voltage distributions make severe changes.

EXAMPLE.- Determine the current through and the voltage across each lamp of group 1 and group 2 in fig. 13 if the neutral wire is opened.

With an open neutral wire, groups 1 and 2 form a series circuit across 248 volts. Since each lamp has a rating of 60 watts and 120 volts, each has a resistance of 240 ohms. The resistance of group 1 is one-sixth of 240 or 40 ohms and the resistance of group 2 is one-half of 240 or 120 ohms. The total resistance, then, is 40 + 120 + 4 or 164 ohms, and the line current is 248 ÷ 164 or 1.512 amps. The current through each lamp of group 1 is 1.512 ÷ 6 or .252 amp, and the voltage across these lamps is .252 × 240 or 60.48 volts. The current through each lamp of group 2 is 1.512 ÷ 2 or .756 amp, and the voltage across these lamps is .756 × 240 or 181.44 volts. Thus the voltage across the lamps in group 1 is below their rated value, causing them to barely glow, and the voltage across the lamps in group 2 is above their rated value, causing them to burn out. In practice, the neutral is never fused, so that such trouble cannot occur.

B & S Gage No.	Area in Circular Mils	Approximate turns per square inch for different types of insulation				B & S Gage No.	Area in Circular Mils	Approximate turns per square inch for different types of insulation					
		Single Cotton	Double Cotton	Enamel	Enamel Single Cotton			Single Cotton	Double Cotton	Enamel	Enamel Single Silk	Single Silk	Enamel Single Cotton
000	167772	-	5.4	-	-	20	1024	775	625	912	812	881	724
00	133079	-	6.8	-	-	21	812	940	750	1150	1000	1065	895
0	105560	-	9	-	-	22	640	1149	910	1429	1225	1330	1072
1	83694	-	11	-	-	23	511	1400	1075	1779	1500	1649	1305
2	66358	-	14	-	-	24	404	1700	1260	2240	1865	2051	1575
3	52624	-	18	-	-	25	320	2050	1505	2820	2300	2540	1905
4	41738	23	22	-	-	26	253	2500	1750	3560	2850	3100	2310
5	33088	29	27	-	-	27	202	3030	2020	4419	3465	3790	2775
6	26244	36	34	-	-	28	159	3669	2305	5579	4220	4710	3345
7	20822	45	42	-	-	29	126	4300	2700	6900	5100	5605	3900
8	16512	55	51	-	-	30	100	5039	3015	8700	6165	6930	4680
9	13087	69	63	-	-	31	79	6919	3460	10700	7345	8472	5275
10	10384	87	79	93	84	32	62	7059	3910	13500	8885	10125	6245
11	8226	108	98	115	104	33	50	8119	4370	17000	10700	12150	7355
12	6529	134	120	145	130	34	40	9600	4870	21100	12800	14350	8310
13	5170	169	149	184	162	35	31	10900	5390	26300	15000	17397	8700
14	4109	210	183	232	197	36	25	12200	6920	32000	17300	20402	10705
15	3260	261	223	292	251	37	20	-	-	39750	20500	23710	-
16	2581	320	271	365	306	38	16	-	-	49350	23500	27495	-
17	2052	397	330	459	374	39	12	-	-	61200	-	-	-
18	1624	492	400	571	463	40	10	-	-	76100	-	-	-
19	1289	593	479	718	562	-	-	-	-	-	-	-	-

TABLE IV

MAGNET WIRE.- Coils are wound with wire insulated by enamel, single or double layers of silk or cotton over bare wire, or single or double layers of silk or cotton over enameled wire. When the space is limited, enamel or single silk covered wire is generally used. Enameled wire costs less. Its insulation has a breakdown temperature of about 550° F and will withstand an electric pressure of 500 volts per mil in thickness. However, this wire must be handled carefully to prevent scratching or cracking the insulation. Where this happens, shorts or grounds may occur. Silk and cotton are injured by charring at a temperature of about 240° F. These materials insulate wire without enamel by spacing it. Wire with either of these insulations will withstand at least 125 volts per mil. The insulating ability of silk and cotton is considerably improved by baking the coil to remove moisture, dipping it in an insulating varnish while it is hot, and then baking it for several hours. When space permits, double cotton covered wire should be used, as its cost is low and its insulation is good after it has been impregnated with varnish.

The number of wires that may be placed in one square inch of cross section is given in Table IV. This data is used extensively in figuring coils.

EXAMPLE.- Determine the cross section of a 200 turn coil wound with No. 18 enamel, single cotton covered wire.

According to Table IV, 453 turns of this wire occupy one square inch. Then 200 turns occupy 200/453 of one square inch or .44 square inch.

HOME WORK

1. What size line wires are required for a motor taking 20 amperes if it is 1000 feet from a 240 volt generator (allow a line drop of 10 per cent)?
2. In problem 1, what size line wires will carry the current without overheating?
3. Twelve lamps, connected as shown in fig. 11, are 400 feet from a 240 volt generator. If each takes 1.5 amperes, what size line wires are required (allow a line drop of 3 per cent)?
4. In fig. 13-1, find the voltage across each load if each lamp takes 2.5 amperes.
5. Solve problem 4, considering the neutral wire broken.

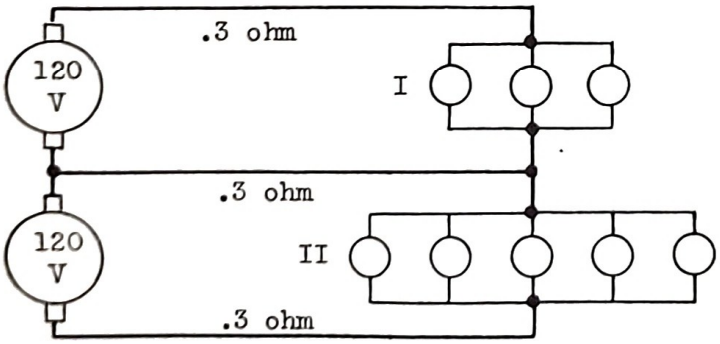


Fig. 13-1

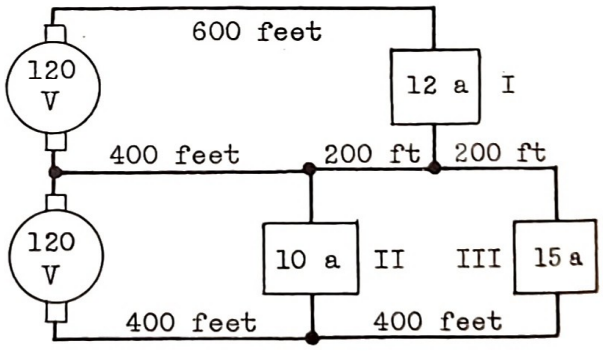


Fig. 13-2

6. Find the voltage across each load in fig. 13-2 if the line wires are No. 8 gage.
7. Determine the height of a coil .6 inch thick if it is wound with 700 turns of No. 16, double cotton covered wire.
8. A coil wound with No. 28, enameled, single silk covered wire has a cross section of .3 square inch. How many turns does it contain?

TEMPERATURE SCALES.- Temperature is expressed in the centigrade scale in some cases and in the Fahrenheit scale in others. It is therefore necessary to be familiar with both and to be able to determine the temperatures on one scale that correspond to those on the other. The two scales are shown in fig. 13-3. Zero and 100 degrees are taken as the freezing and the boiling points respectively on the centigrade scale, while 32 and 212 are taken on the Fahrenheit scale. Between these two points, then, the centigrade scale has 100 divisions and the Fahrenheit scale has 180 divisions. Consequently, a centigrade reading is 5/9 of the reading for the same temperature on the Fahrenheit scale. To determine a centigrade temperature (C) corresponding to a Fahrenheit temperature (F), subtract 32 and multiply by 5/9. That is,

$$C = \frac{5}{9}(F - 32)$$

To determine a Fahrenheit temperature corresponding to a centigrade temperature, multiply by 9/5 and add 32. That is,

$$F = \frac{9}{5}C + 32$$

EXAMPLE.- What temperature in degrees centigrade corresponds to 68 degrees Fahrenheit?

$$C = \frac{5}{9}(68 - 32) = 20°$$

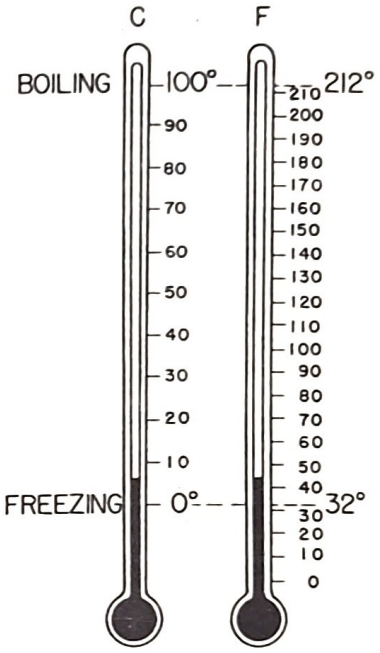


Fig. 13-3
Thermometer scales

CHANGE IN RESISTANCE DUE TO A CHANGE IN TEMPERATURE.- The resistance of pure metals, such as silver, copper, aluminum, etc., increases as the temperature becomes greater. Some alloys, such as constantan and manganin, change very little in resistance, and these are used in measuring instruments, where it is desired to have the resistance of coils remain constant so that the instruments indicate accurately. The resistance of carbon and electrolytes decreases with a rise in temperature.

The amount by which the resistance of a substance changes per degree change in temperature for each ohm of resistance at 0° C is called the temperature coefficient of resistance. For pure metals, this coefficient (denoted by the letter "a") has a value of approximately .004 (see Table I).

Letting R_o represent the resistance at 0° C, then $R_o a$ is the change in resistance for one degree rise in temperature, while $R_o at$ is the change in resistance for t degrees rise in temperature.

Then the final resistance (R_f) will equal the resistance at 0° C, which is R_o, plus the change in resistance ($R_o at$). That is,

$$R_f = R_o + R_o at \qquad (24)$$

EXAMPLE.- The resistance of a nichrome heating element is 50 ohms at 0° C. What is its resistance at 1300° C?

According to Table I, the value of "a" for nichrome is .0004. Then

$$R_f = 50(1 + .0004 \times 50) = 51 \text{ ohms}$$

In some problems it is necessary to determine the final resistance when a change in temperature occurs from a value other than 0° C. This may be done without first finding the resistance at 0° C, as would be required by using equation 24.

Letting R_i equal the initial resistance and t_i the initial temperature, then

$$R_i = R_o(1 + at_i) \tag{25}$$

Solving for R_o in equation 25 and substituting its value in equation 24, we have

$$R_f = \frac{R_i(1 + at_f)}{(1 + at_i)} \tag{26}$$

EXAMPLE.- The resistance of a coil wound with iron wire is 200 ohms at 20° C. What is its resistance at 80° C?

$$R_f = \frac{200(1 + .006 \times 80)}{(1 + .006 \times 20)} = 264.3 \text{ ohms}$$

It is sometimes necessary to determine the temperature rise that a machine undergoes when started and run at full load for a long period of time. This may be done by measuring its resistance before starting the motor, at a room temperature of 20° C, and again after the run. Then, substituting in equation 26, we have

$$t_f - t_i = (\frac{1}{a} + t_i)\frac{R_f - R_i}{R_i} \tag{27}$$

EXAMPLE.- The winding of a motor has a resistance of 10 ohms when the machine is started and has a resistance of 10.5 ohms after it has run several hours at full load. If the room temperature is 20° C, what is the temperature rise of the winding?

$$t_f - t_i = (\frac{1}{.0041} + 20)(\frac{12 - 10}{10}) = 52.8 \text{ degrees}$$

HOME WORK

1. Express the following temperatures in degrees centigrade: (a) 72° F, (b) 100° F, (c) 50° F.
2. Express the following temperatures in degrees Fahrenheit: (a) 20° C, (b) 68° C, (c) 12° C.
3. The resistance of a copper wire is 3 ohms at 0° C. What is its resistance at 20° C?
4. The resistance of a coil of nichrome wire is 100 ohms at 20° C. What is its resistance at 200° C?
5. The resistance of a transformer winding is .4 ohm at room temperature (20° C). After the transformer reaches its maximum temperature, its resistance is .46 ohm. Determine the rise in temperature.
6. A winding in a motor has a resistance of 100 ohms at a temperature of 80° F. If the resistance of this winding increases to 120 ohms, what is its temperature rise?
7. When cold, an electric furnace with a nichrome heating element takes 100 amperes at 240 volts. After it is hot, the current drops to 90 amperes. What is the temperature of the furnace if the room temperature is 20° C?

WIRING METHODS.- While a large number of wiring methods are permitted by the National Electric Code, many of these are seldom employed in practice because of poor appearance, lack of durability, high cost of installation, etc. In the following pages we will consider only the wiring methods in common use, such as wiring with rigid conduit, electric metallic tubing, flexible conduit, armored cable, leaded armored cable, non-metallic sheathed cable, and surface metal raceway.

RIGID CONDUIT.- A rigid conduit wiring system is one in which the conductors are installed in iron or steel pipes and attached equipment (see fig. 14). These pipes are called conduit. A good grade has both the interior and the exterior coated with zinc and enamel. This grade should be used in damp places and in concrete. A less expensive grade has its interior and exterior surfaces coated with either enamel or zinc, or has its interior surface coated with zinc and its exterior surface coated with enamel. Rigid conduit has the same dimensions and thread size as gas pipe, but is softer and therefore can be bent more easily. The Code requests that the radius of the inner edge of any bend be not less than six times the internal diameter of the conduit. If the radius of the bend is made smaller than this, the conduit is apt to be injured or its internal diameter reduced. The actual diameter of conduit is slightly greater than the so-called size. This is shown in Table V.

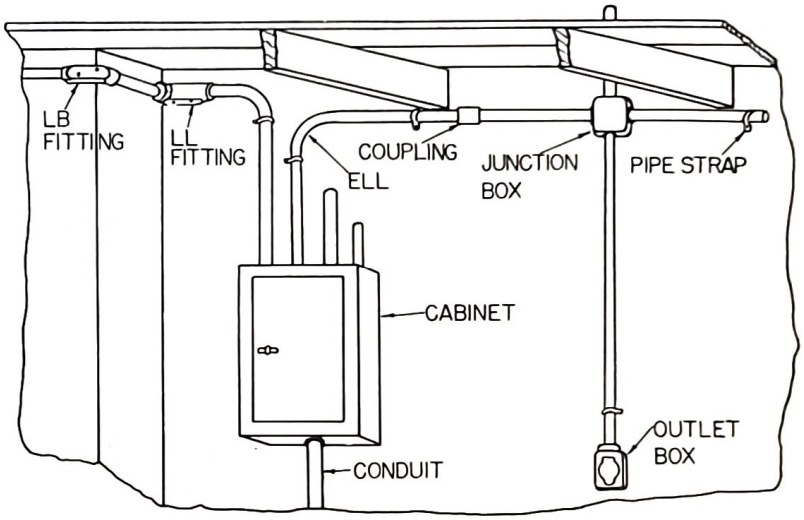


Fig. 14 Example of a conduit installation

SIZE OF CONDUIT	INTERNAL DIAMETER IN INCHES	INTERNAL AREA IN SQUARE INCHES
1/2	.622	.3
3/4	.824	.53
1	1.049	.86
1-1/4	1.380	1.5
1-1/2	1.610	2.04
2	2.067	3.36
2-1/2	2.469	4.79
3	3.068	7.38

TABLE V

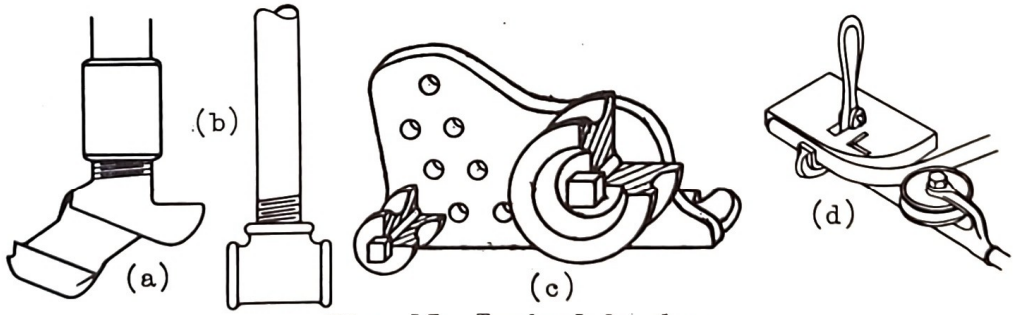


Fig. 15 Typical benders

BENDERS.- Various devices for bending conduit are manufactured. Some of the most common types are shown in fig. 15. The bender shown in fig. 15a is commonly called a hickey and is used for bending small size conduit. A hickey may be made by screwing a one inch pipe, about $3\frac{1}{2}$ feet long, into a tee (fig. 15b). This hickey is less suitable than the one shown in fig. 15a, because the head cannot be put around the conduit from the side, but must be put in place from the end. Then, too, it produces kinks unless it is shifted frequently while making a bend. For bending large size conduit, the benders shown in figs. 15c and 15d are generally used.

MAKING A RIGHT ANGLE BEND.- To make a right angle bend with the hickey shown in fig. 15a, proceed as follows: Measure from the point where the conduit is to start to the outside of the bend to be formed, and then lay off this distance from a wall.

This is indicated by the line in fig. 16a. Then place one end of the conduit against the wall and slip the hickey over the other end to a point about two inches beyond the line. Next stand on the conduit with one foot where the bend is to start and pull on the bender until the end beyond the bend forms a small angle (fig. 16b). Now slide the head of the hickey slightly nearer the wall and bend further. Continue this procedure until the outer edge of the raised portion aligns vertically with the line drawn on the floor (fig. 16c).

If the vertical portion of the conduit lies beyond the line, slip the hickey from its last position so that it is about 3/4 of an inch nearer the wall, and bend the conduit further (fig. 17a). Next turn the head around and move it near the center of the bend (fig. 17b), and then pull up on the handle until the raised section is vertical.

If the raised end falls short of the line, place the hickey at about the center of the bend (fig. 17c) and pull up on the handle. Then turn the head of the hickey around, move it up the pipe, and pull down until the raised section is vertical.

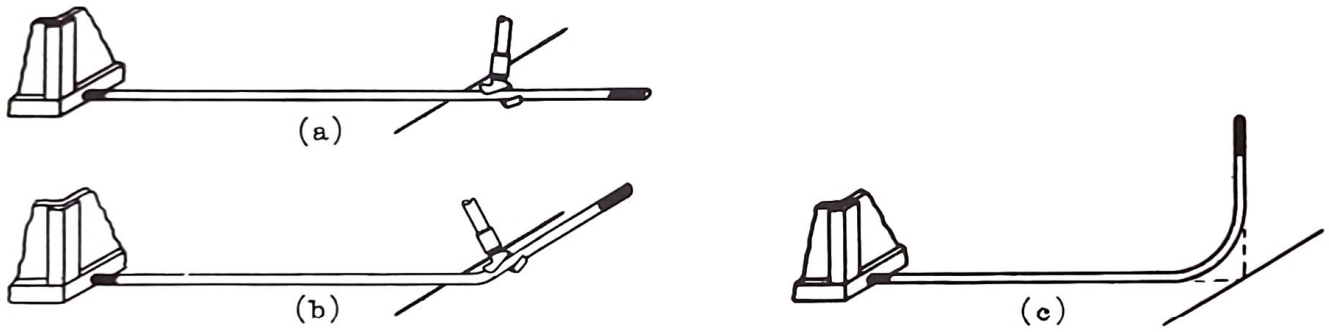


Fig. 16 Steps in making a bend

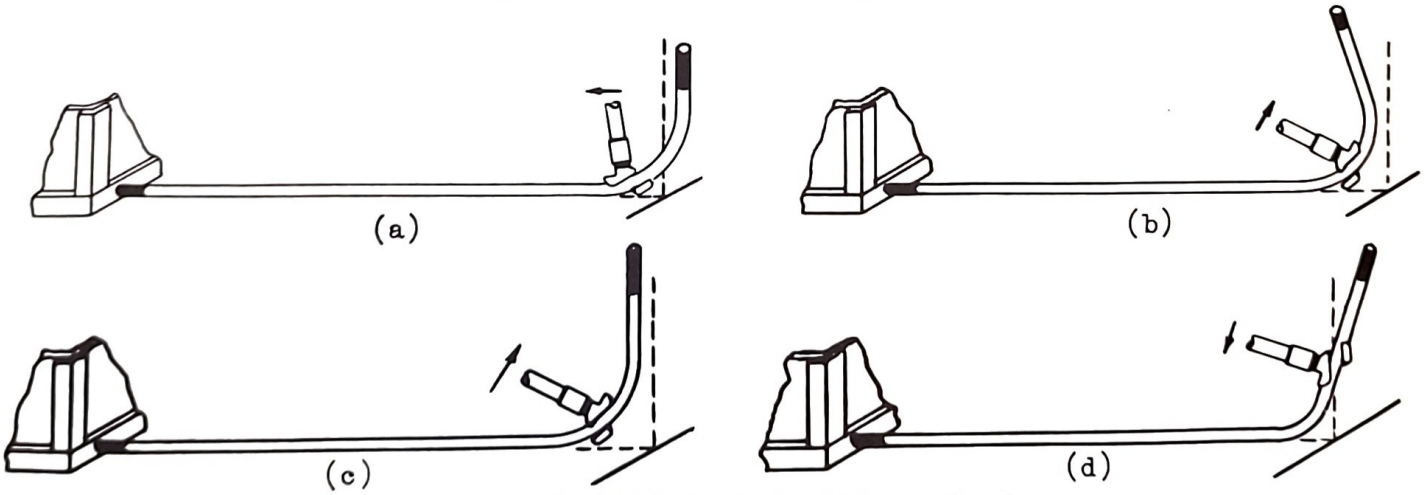


Fig. 17 Method of shifting a bend

END BEND.- It is sometimes necessary to have a small radius bend at the end of a conduit run, threaded as near the bend as possible (fig. 18a). To make such a bend, a coupling is first screwed on to prevent injury to the threads. Then a small radius bend is made near the end and the coupling used in protecting the threads is removed.

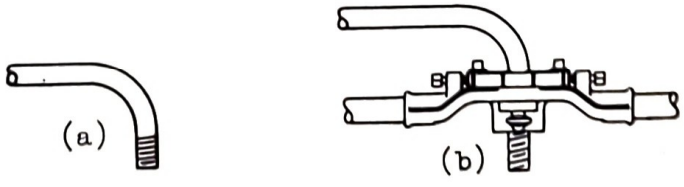


Fig. 18 Method of making an end bend

Next the die in the stock is reversed (fig. 18b) and the conduit is threaded to the bend. The die is then removed and the surplus length cut off.

REAMING.- After a piece of conduit has been cut, its ends should be reamed to remove the burr formed by the cutting (fig. 19). If this is not removed, it will probably injure the insulation on the conductors when they are drawn into the conduit. The burr is usually removed from small conduit by a reamer (fig. 19), which is turned by a brace, and from large conduit by means of a half-round file.

Fig. 19
Reaming conduit

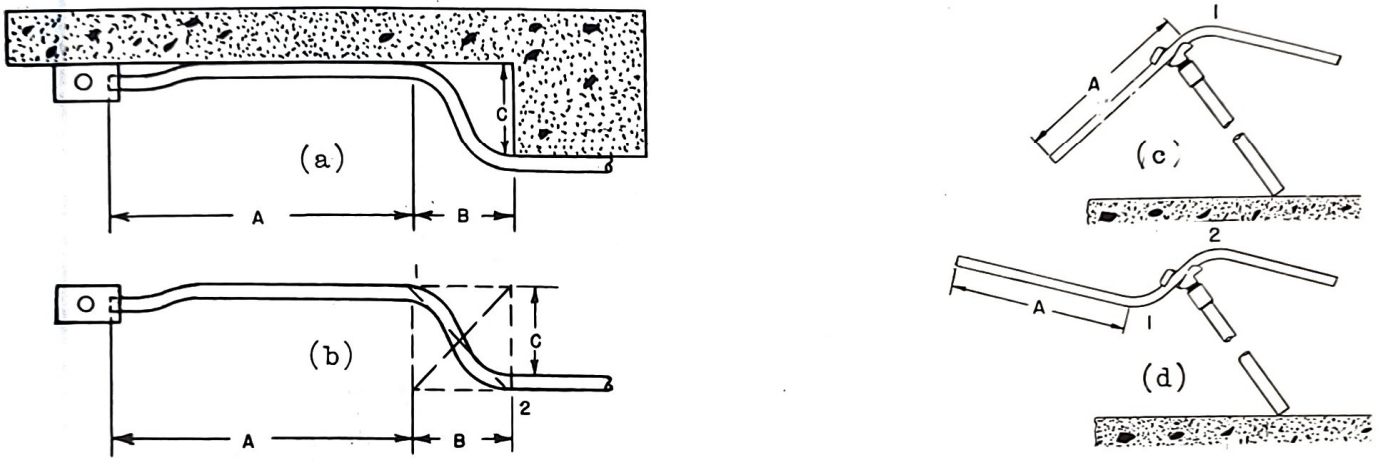
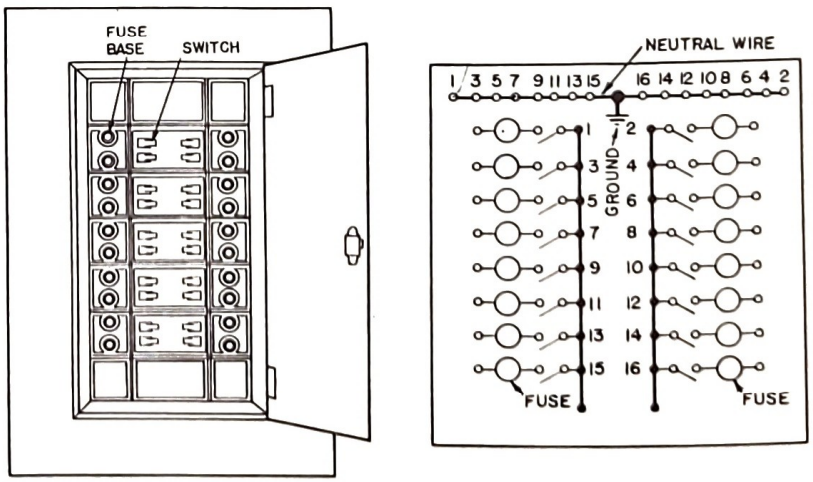


Fig. 20 Steps in making an offset

MAKING AN OFFSET.- Fig. 20a shows a properly made offset. The distance within which the bends fall, which is indicated by B, should be as short as possible if the conduit is exposed, but the radius of each bend should not be less than that permitted by the Code. A convenient way of making the offset shown in fig. 20a is to make the measurements A, B, and C. Then mark these measurements on the floor and draw the additional lines shown in fig. 20b. The run must lead up to 1, extend diagonally to 2, and then extend parallel to the straight section to 1 as shown in fig. 20b. To make the first bend, mark off the distance A from one end of the conduit, slip on the hickey so that it will line up with this mark, place it in the position shown in fig. 20c, and then press down on the unmeasured end of the conduit until the bend is found to pass through the center of the rectangle in fig. 20b. Next slip the conduit to the point where the second bend begins, turn the unmeasured end upward, and pull down on this end until the offset is complete (see fig. 20d).

EQUIPMENT USED IN CONDUIT SYSTEMS.- Conduit must always be fastened rigidly in place, and its ends must be connected to cabinets, boxes, or fittings.



(a) (b)

Fig. 21 Typical lighting cabinet

CABINETS.- A cabinet is made of sheet steel and encloses a panel board on which branch circuits are connected to a feeder. Surrounding the cabinet is a wiring gutter to house the section of the conductors extending from the conduit to the fuses. Fig. 21a shows a three wire lighting cabinet. It has a grounded unfused neutral, as shown in fig. 21b. Fig. 22a shows a power cabinet, in which the switch blades are mounted on the doors. When a door is opened (fig. 22b), a circuit, together with its fuses, is entirely disconnected from the feeders (fig. 22c). With this construction, then, no live parts are exposed. If it is desired to keep the branch circuit disconnected, the switch blades are changed to the "off" position, as shown in fig. 22d.

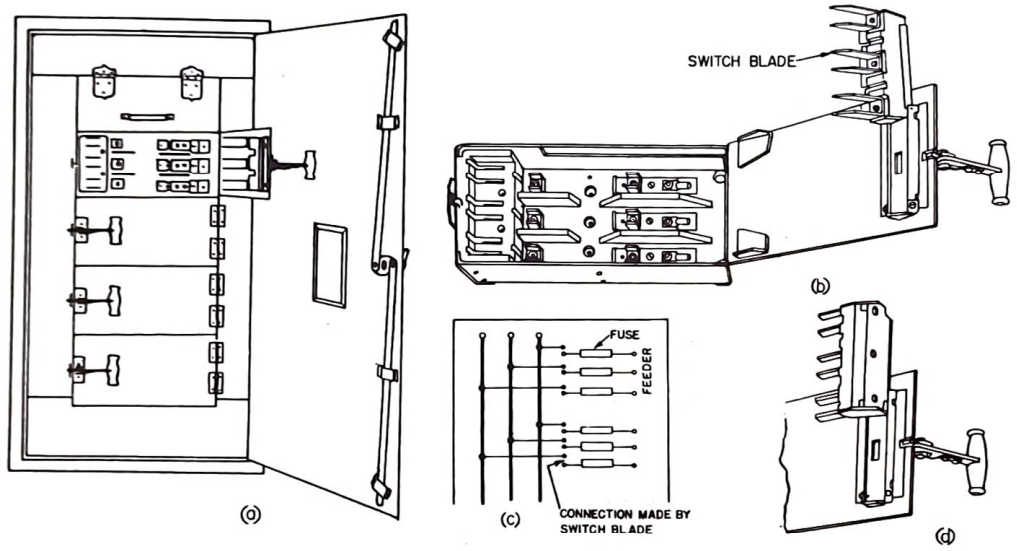


Fig. 22 Typical power cabinet

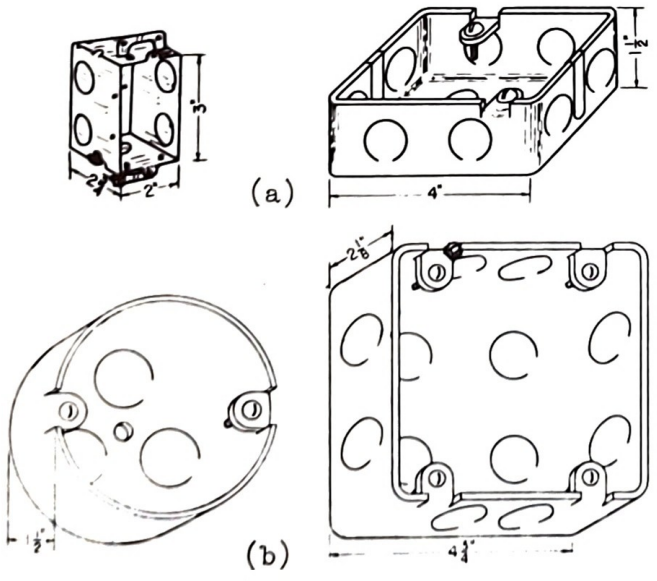


Fig. 23 Standard boxes

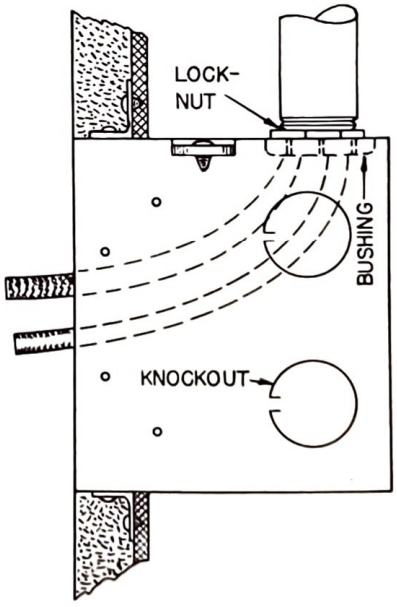


Fig. 24 Method of installing outlet box

BOXES.- Conduit systems contain both junction and outlet boxes. A junction box is placed where several conduit runs intersect (see fig. 14). It provides means for pulling in the wire and serves as an inclosure for the connections that must be made.

Junction boxes metallically connect conduit runs, making it possible to ground the entire system with one ground connection. They are also used as outlet boxes. For half inch conduit, these boxes are generally made in two sizes, as shown in fig. 23a.

An outlet box (fig. 23b) may be used to inclose a switch which controls the current in a circuit, or can be fitted with a special cover through which light and power loads can be connected.

For concealed work, all boxes should be mounted so that their outer edges are flush with the wall surface (fig. 24).

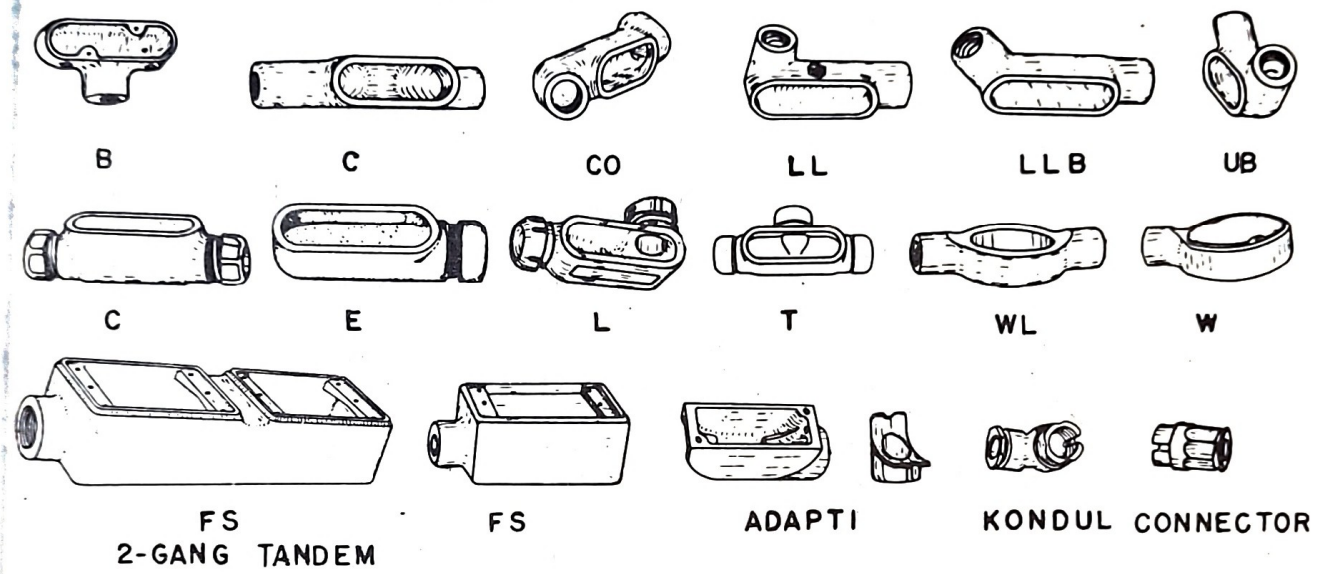


Fig. 25 Common types of fittings

FITTINGS.- Some common types of conduit fittings are shown in fig. 25. They are called by various names, such as condulets, unilets, and pipe taplets. These fittings are made with two types of projections. One type has a female pipe thread so that it can be screwed directly to a threaded piece of conduit. The other has a projection which is fastened to a threadless piece of conduit (fig. 26). The use of fittings with such projections is increasing because of a considerable saving in time. Both types are shown in fig. 25.

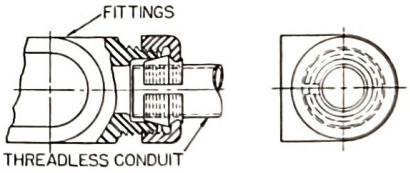
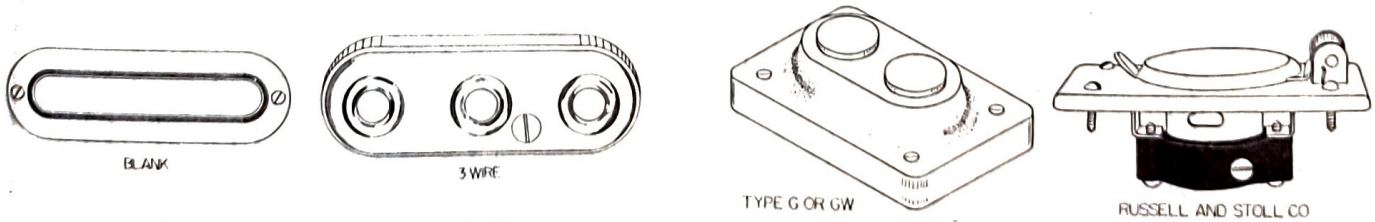


Fig. 26 Fitting with a threadless connector

The principal difference between a box and a fitting is a difference in construction that makes it necessary to use different methods of attaching conduits to them. In many cases the two serve the same purpose. Both are used for exposed work but fittings are preferable because they are more nearly water-tight, occupy less space, and are more attractive.



(a) (b) (c) (d)

Fig. 27 Blank cover, 3 wire cover, switch, and plug

If an attempt is made to push a tape through a conduit run that contains a large number of bends, the tape frequently buckles at one of the bends as shown in fig. 34. Even if the tape is pushed through, it becomes difficult to pull in the wire because each bend increases the friction between the wire and the conduit. For this reason, the Code specifies that a run between boxes or fittings must not have more than the equivalent of four right angle bends.

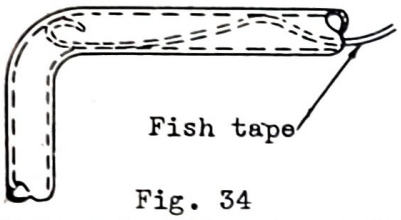


Fig. 34
Fish tape buckling in conduit

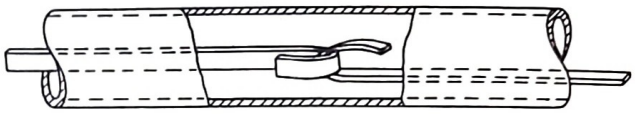


Fig. 35
Fishing from both ends of a conduit run

If a fish tape cannot be pushed through from one end, a second tape may be pushed in from the other end until it comes in contact with the first and then manipulated until the two hook ends of the tapes engage (fig. 35). After this, the first tape is pulled through by the second.

The connection between the conductors and the fish tape must not give way when stress is applied and must offer a negligible amount of friction when the conductors are drawn into the conduit. An excellent method of attaching two conductors to a fish tape so as to satisfy these requirements is illustrated in fig. 36. The second conductor is attached to the first (fig. 36a), the first conductor is attached to the fish tape (fig. 36b), and the joint is taped.

If twin conductors are to be pulled through a somewhat straight and short run, the conductors may be attached to the tape as shown in fig. 37. The connection is made by cutting a slit in the braid and hooking the fish tape in it. This method of connecting the conductors should be used when possible, as it saves time.

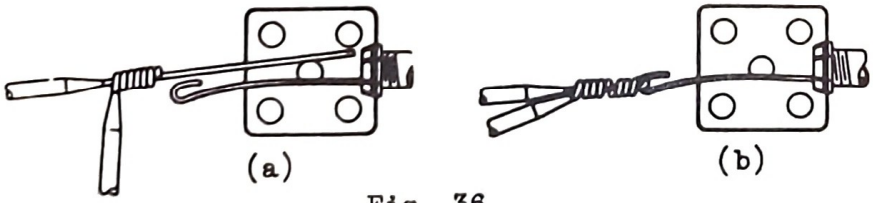


Fig. 36
Another method of attaching conductors to a fish tape

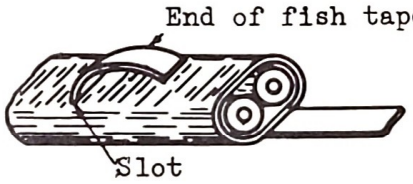


Fig. 37
Quick method of connecting conductors to a fish tape

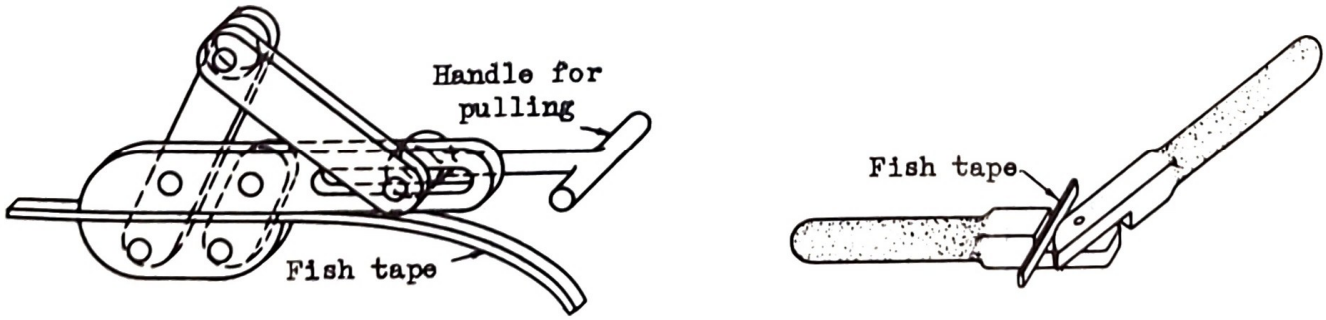


Fig. 38 Fish tape pullers

PULLING CONDUCTORS INTO THE CONDUIT.- Conductors are usually drawn into the conduit by one person pulling the fish tape out at one end and another forcing the conductors in at the other end. If the pull is hard, the tape is pulled out by means of a pair of pliers or, preferably, by means of a fish tape puller (fig. 38).

SIZE OF CONDUCTOR	MINIMUM SIZE IN INCHES OF CONDUIT FOR 1 TO 9 CONDUCTORS								
	1	2	3	4	5	6	7	8	9
No. 14	1/2	1/2	1/2	1/2	3/4	3/4	3/4	1	1
12	1/2	1/2	1/2	3/4	3/4	1	1	1	1-1/4
10	1/2	3/4	3/4	3/4	1	1	1-1/4	1-1/4	1-1/4
8	1/2	3/4	1	1	1-1/4	1-1/4	1-1/4	1-1/4	1-1/2
6	1/2	1	1-1/4	1-1/4	1-1/2	1-1/2	2	2	2
5	3/4	1-1/4	1-1/4	1-1/4	1-1/2	2	2	2	2
4	3/4	1-1/4	1-1/4	1-1/2	2	2	2	2	2-1/2
3	3/4	1-1/4	1-1/4	1-1/2	2	2	2	2-1/2	2-1/2
2	3/4	1-1/4	1-1/2	1-1/2	2	2	2-1/2	2-1/2	2-1/2
1	3/4	1-1/2	1-1/2	2	2	2-1/2	2-1/2	3	3
0	1	1-1/2	2	2	2-1/2	2-1/2	3	3	3
00	1	2	2	2-1/2	2-1/2	3	3	3	3-1/2
000	1	2	2	2-1/2	3	3	3	3-1/2	3-1/2
0000	1-1/4	2	2-1/2	2-1/2	3	3	3-1/2	3-1/2	4

TABLE VI

METHOD OF DETERMINING SIZE OF CONDUIT.- According to the Code, the size of rigid conduit required for a given number of conductors of the same size is given in Table VI.

If the conductors are of different sizes, the sum of their total areas, expressed as a percentage of the internal area of the conduit, should not exceed the values given in Table VII. The area over the braid of rubber covered conductors is given in Table VIII.

NUMBER OF WIRES	% OF TOTAL AREA IN CONDUIT THAT MAY BE OCCUPIED BY CONDUCTORS
1	53
2	31
3	43
4 or over	40

TABLE VII

SIZE OF CONDUCTORS	APPROXIMATE AREA OF BRAID IN SQUARE INCHES
14	.031
12	.038
10	.045
8	.071
6	.13
4	.16
2	.21
1	.27
0	.31
00	.35
000	.41
0000	.48

TABLE VIII

EXAMPLE.- Determine the size of the conduit needed for a run using four No. 6 gage wires, three No. 8 gage wires, and two No. 12 gage wires.

According to Table VIII, the cross-sectional area of the conductors for this conduit is (4 × .13) + (3 × .071) + (2 × .038) or .809 square inch.

By Table VII, the internal area of the conduit must not be less than .809 ÷ .40 or 2.02 square inches. A 1-1/2 inch conduit has an internal area of 2.04 square inches (see Table V), and is therefore large enough for the conductors.

1. (a) What is the internal diameter of a 1/2 inch conduit? (b) Of a 1-1/4 inch conduit?

2. Give the least radius permitted by the Code for the inner edge of a bend made in (a) a 1/2 inch conduit? (b) A 1 inch conduit? (c) A 2 inch conduit?

3. Give the steps that should be taken in making a short radius end bend.

4. Where should the conduit system of wiring be used?

5. For what purpose are fittings preferable to boxes?

6. Explain (a) one way fishing; (b) two way fishing.

7. When is two way fishing used?

8. What is the maximum number of right angle bends permitted by the Code between two outlets in a conduit run?

9. How many No. 14 wires may be pulled into conduits of the following sizes: (a) 1/2 inch; (b) 1 inch; (c) 1-1/2 inch.

10. What size conduit is required for (a) five No. 4 wires? (b) eight No. 14 wires? (c) six No. 8 wires?

11. (a) What size conduit is required for two No. 3 and five No. 14 wires? (b) For three No. 6, four No. 10, two No. 12, and eight No. 14 wires?

12. What size line wires and conduit are required for a motor that takes 50 amperes at full load?

13. Determine the size of the line wires and conduit required by a 230 volt, 100 horsepower motor which has an efficiency of 85 per cent.

ELECTRIC METALLIC TUBING.- Electric metallic tubing resembles rigid conduit. It has the same internal diameter, but has a thinner wall, making the outer diameter smaller. This tubing will therefore carry the same number of wires as rigid conduit. The wall thickness for metallic tubing is too thin to be threaded and the connections are made by threadless fittings similar to those used with rigid conduit. Metallic tubing may be installed wherever rigid conduit is permitted, except where it may be subject to severe mechanical injury.

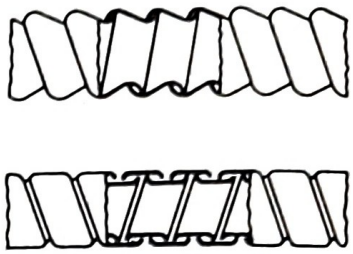


Fig. 39 Two types of flexible conduit

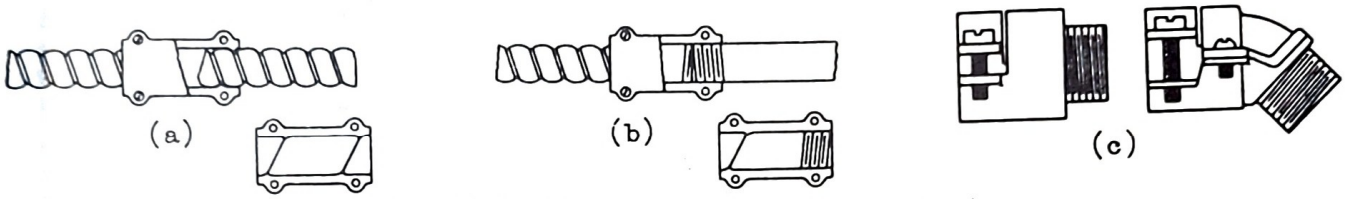


Fig. 40 Fittings for flexible conduit

FLEXIBLE CONDUIT.- As shown in fig. 39, flexible conduit consists of one or two steel strips wound spirally, with interlocked edges, to form a steel tube that can be bent easily. This conduit is much easier to install than rigid conduit because the desired bends are easily formed by hand and couplings are seldom required, since it is manufactured in lengths ranging from 50 to 250 feet. Some common types of fittings for flexible conduit are shown in fig. 40. Flexible conduit, electric metallic tubing, and non-metallic sheathed cable may be connected to rigid conduit boxes by means of connectors. A connector for flexible conduit is shown in fig. 41.

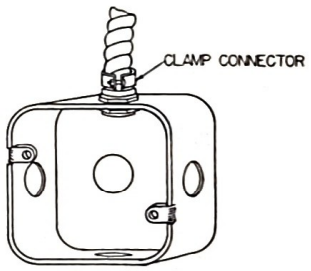


Fig. 41 Flexible conduit connector

Flexible conduit may be used in both concealed and exposed work, but must not be used in damp places, because it is not waterproof. When the run is in the same direction as the joists, the conduit should be fastened to the sides of the joists with straps. When the run is at right angles to the joists, the conduit should be run through holes bored through the centers of the joists (as shown in fig. 42).

Flexible conduit is used chiefly for wiring and making extensions in finished buildings. It is also used for extensions to portable and movable equipment and short lengths are used between stationary motors and rigid conduit. Its use in the latter case makes it possible to shift a motor slightly to tighten a belt or chain, or to mesh gears accurately.

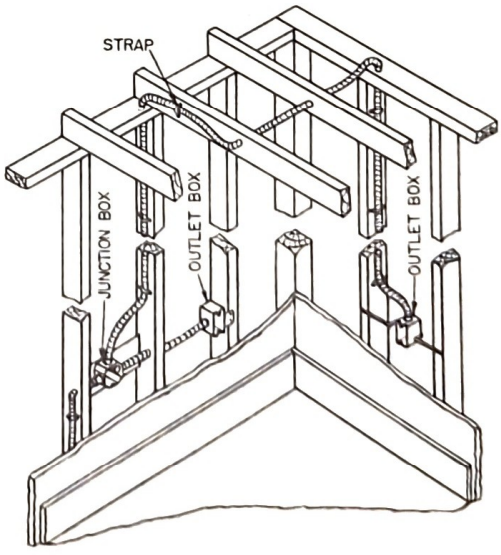


Fig. 42 Section of a flexible conduit system

ARMORED CABLE.- Armored cable, generally known as BX, consists of rubber insulated wire covered with an armor that has the same appearance as flexible conduit. This armor protects the wire from injury and to a slight extent from moisture. It is installed in the same manner as flexible conduit, except that about 8 inches of the armor must be stripped from the end before connecting to a box.

The procedure is as follows: Using a fine tooth hack saw, the armor is cut as shown in fig. 43a, about 8 inches from its end, being careful not to injure the insulation on the wire. The 8 inch end is then broken off by bending it back and forth. The sharp edges are filed smooth and the wire insulation is protected by means of a fiber bushing (fig. 43b). The cable is then attached to the box in the same manner as flexible conduit. It must not be used in places subject to excessive humidity.

Armored cable is also made with a lead sheet between the rubber insulated conductors and the armor. Such cable is commonly referred to as BXL and may be used in places that are permanently damp, as in masonry, in the fill of buildings, and in underground runs. Both BX and BXL must contain no joints and splices between outlets.

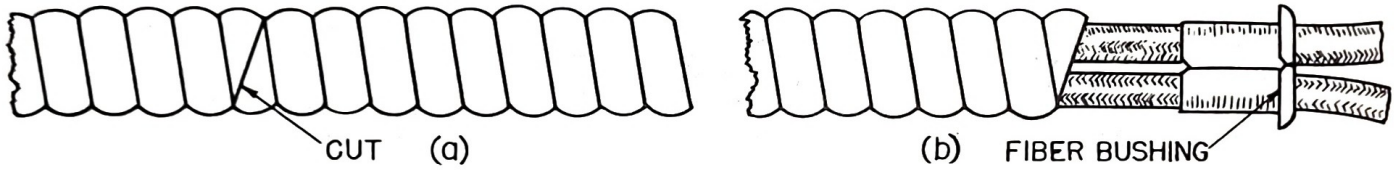


Fig. 43
Method of cutting armor and protecting conductors of armored cable

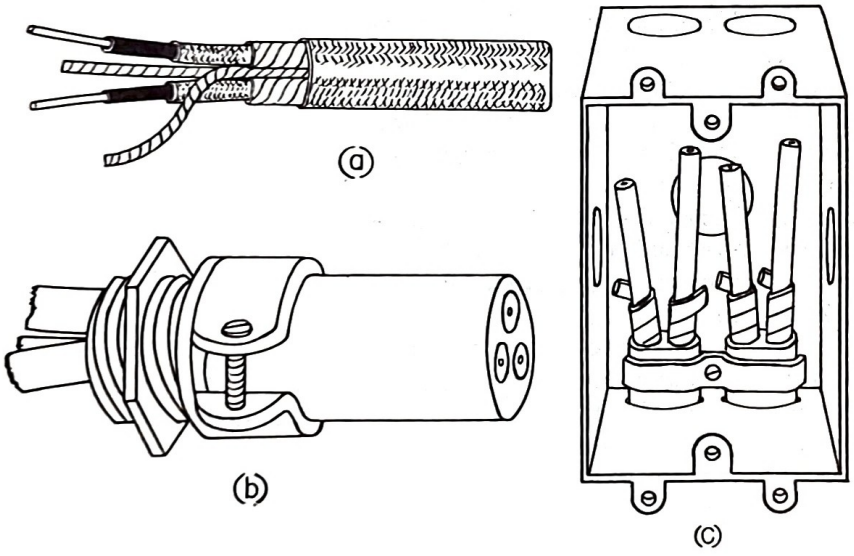


Fig. 44 Types of connectors used with non-metallic sheathed cable

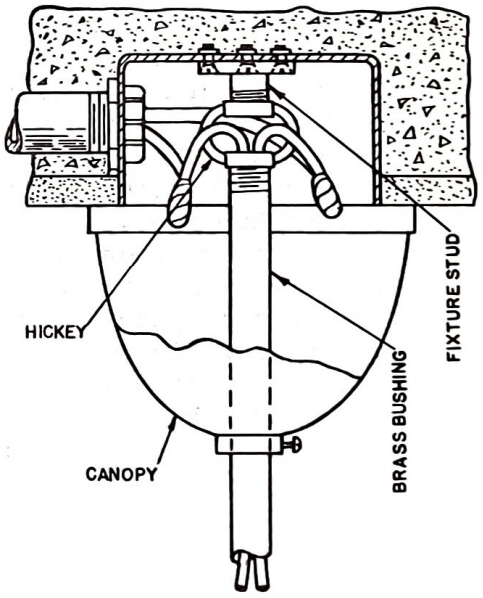


Fig. 45 Fixture installation

NON-METALLIC SHEATHED CABLE.- A common type of non-metallic sheathed cable is shown in fig. 44a. It is manufactured with either two or three wires. In one construction, one wire is not insulated and is used for grounding outlet boxes. The outer braids are impregnated with a moistureproof and fire-resisting compound.

Non-metallic sheathed cable is installed in the same way as armored cable and similar box connectors may be used with it (fig. 44b). Boxes with attached connectors are generally used, however, as shown in fig. 44c.

This wiring system may be exposed or concealed in air spaces between walls. It should not be used in damp places nor be buried in plaster or concrete. This wiring method is widely used for house wiring because of its low cost.

With any of the wiring methods considered, ceiling fixtures are installed as shown in fig. 45.

SURFACE METAL RACEWAY.- Surface metal raceway, also called metal molding, consists of a metal strip with edges that bend around a slightly curved base (fig. 46). This raceway requires the use of special boxes and fittings, some of which are shown in fig. 47. Fig. 48 illustrates how easily metal molding can be installed. One end of a piece of raceway is slipped on a projection on the box base and the other end is slipped on one end of an elbow.

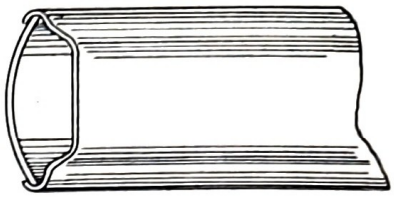


Fig. 46
Surface metal raceway

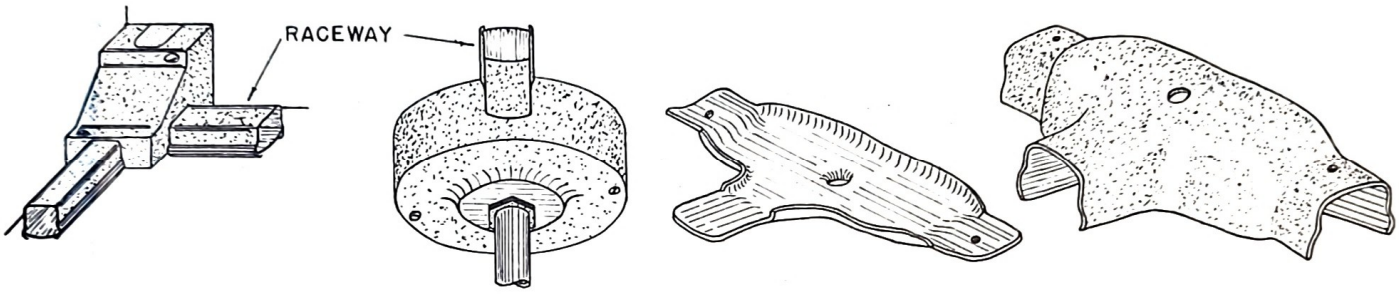


Fig. 47
Surface metal raceway boxes and fittings

Another piece of raceway is slipped on the other end. Then the box and elbow are fastened with screws. The wire is pulled into the raceway, and after the desired connections are made, the box cover is fastened with screws and the elbow cover is snapped on.

Metal raceway may be used only in dry places. It may extend through walls, partitions, and dry floors, providing the molding is not broken in passing it through. It is used principally in wiring old buildings and in making extensions. For exposed work, surface metal raceway is preferable to other materials, because it has a much better appearance.

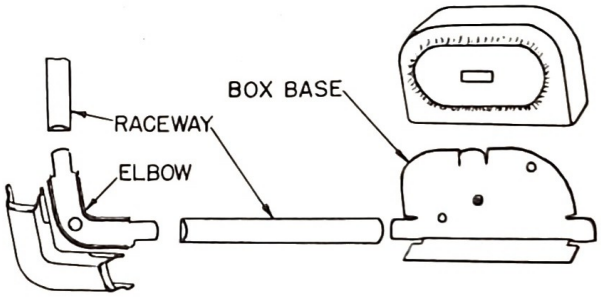


Fig. 48
Method of installing surface metal raceway

INSULATION.- Rubber is in more general use as an insulating material than any other substance, because it is a good insulator, is very tough, is waterproof, and is cheap. Rubber covered wire (type R) may be used in all installations except those where the temperature exceeds 120° F. Rubber deteriorates very slightly below this temperature but very rapidly above it, becoming brittle and breaking easily. For temperatures above 120° F, varnished cambric or asbestos covered wire should be used.

Varnished cambric insulation (type VC) consists of a cotton tape impregnated with insulating varnish, which is wrapped several times over the conductor. This may be used where the temperature does not exceed 167° F. Because of the higher permissible temperature, the current carrying capacity of varnished cambric wire is about 20 per cent higher than the capacity of rubber covered wire (see Table III).

Varnished cambric is not as easily injured by oil as is rubber. It is an excellent type of insulation and is frequently used on wires subject to high voltages.

Conductors insulated with a braid of asbestos should be used in hot dry places where other types of insulation would be damaged. Wire with this insulation (type A) is used for leads on heating elements and mogul type lamp sockets, and on the back of large switchboards. It should never be used for exterior wiring or in a place where moisture is present.

Slow burning wire (type SB) has three braids of cotton impregnated with a material that has both insulating and fire-resisting properties. This insulation will not withstand the temperatures that asbestos will withstand, but it is used for about the same purposes.

FLEXIBLE CORDS.- Some of the most common types of cords used in wiring pendants and portable equipment are lamp cord, reinforced cord, hard service cord, and heater cord. The conductors in these types consist of stranded wire wrapped with thread to keep the broken strands from punching through the insulation.

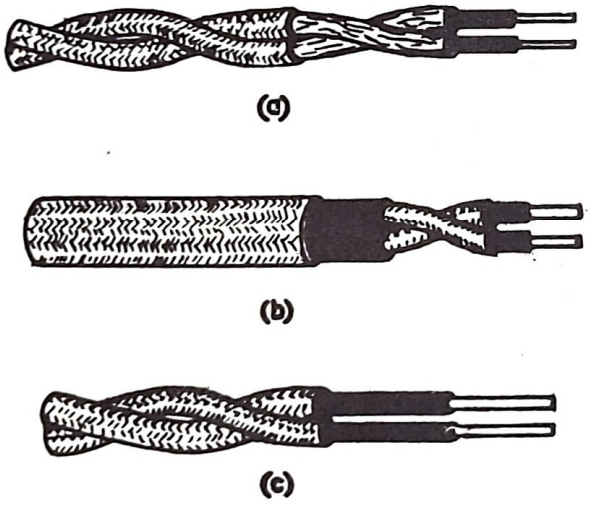


Fig. 49
Common types of cords

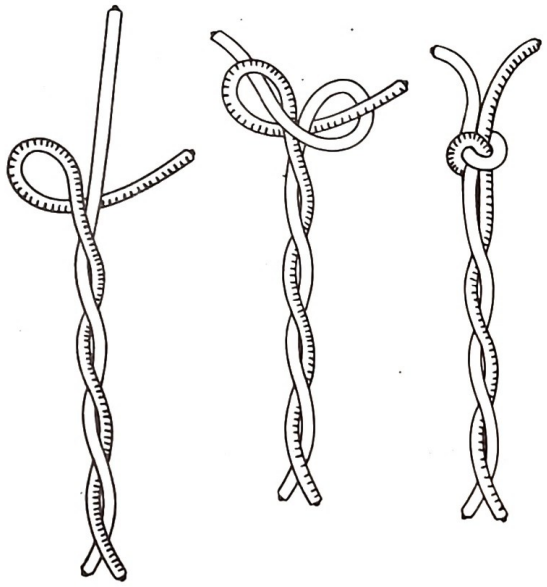


Fig. 50
Method of tying an underwriter's knot

Lamp cord consists of two conductors covered with rubber and a cotton braid, which are twisted together (fig. 49a). This cord (type C) may be used in dry places, where it is not subject to hard usage. Lamp cord is not highly recommended for any use, reinforced cord being preferred instead.

Reinforced cord (type P) is the same as lamp cord, but has, in addition, a rubber jacket applied over the two conductors (the jacket being covered with a cotton or silk braid (fig. 49b). This cord is also recommended for use in dry places where it is not subject to severe treatment, as in residences and office buildings.

Hard service cords (known as type SJ and type S) are recommended for hard usage. Both of these consist of rubber insulated conductors which have been twisted together and covered with a special high grade rubber (fig. 49c). Type SJ is not approved for factories, garages, or outside use. Type S differs from type SJ only in that it has a heavier outer cover. Type S cord may be used anywhere as long as the temperature does not exceed 120° F.

For portable heating equipment, heater cord must be used. Each conductor of this cord is covered with a 1/64 inch thickness of rubber, followed by a covering of asbestos. This may or may not be covered with a cotton braid.

UNDERWRITER'S KNOT.- The portion of a cord extending within a socket, plug, or fitting should be installed so that any stress imposed on it will not be transmitted to joints or binding screws. This condition is fulfilled by tying an underwriter's knot at the end of the cord, as shown in fig. 50. Such a knot can stand considerable stress without injury to the insulation.

SWITCHES.- Manually operated switches used in lighting and low power circuits are of three types: knife, snap, and flush. Knife switches may be single, double, or three pole, and may be single or double throw (fig. 51). A single pole switch disconnects one line wire, a two pole switch disconnects two, etc. Snap and flush switches (fig. 52) may be single pole, double pole, three way, or four way.

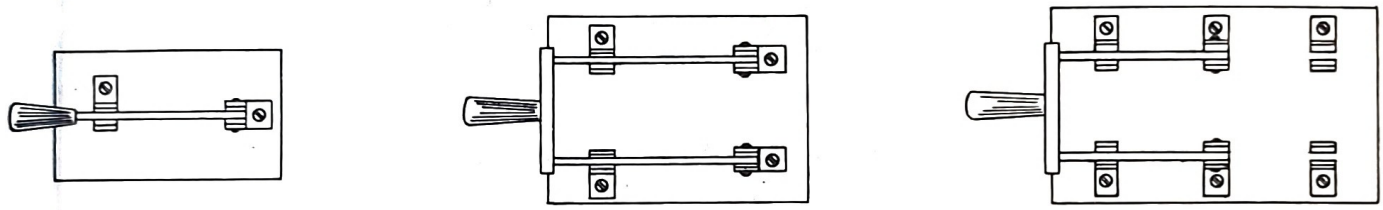


Fig. 51 Knife switches

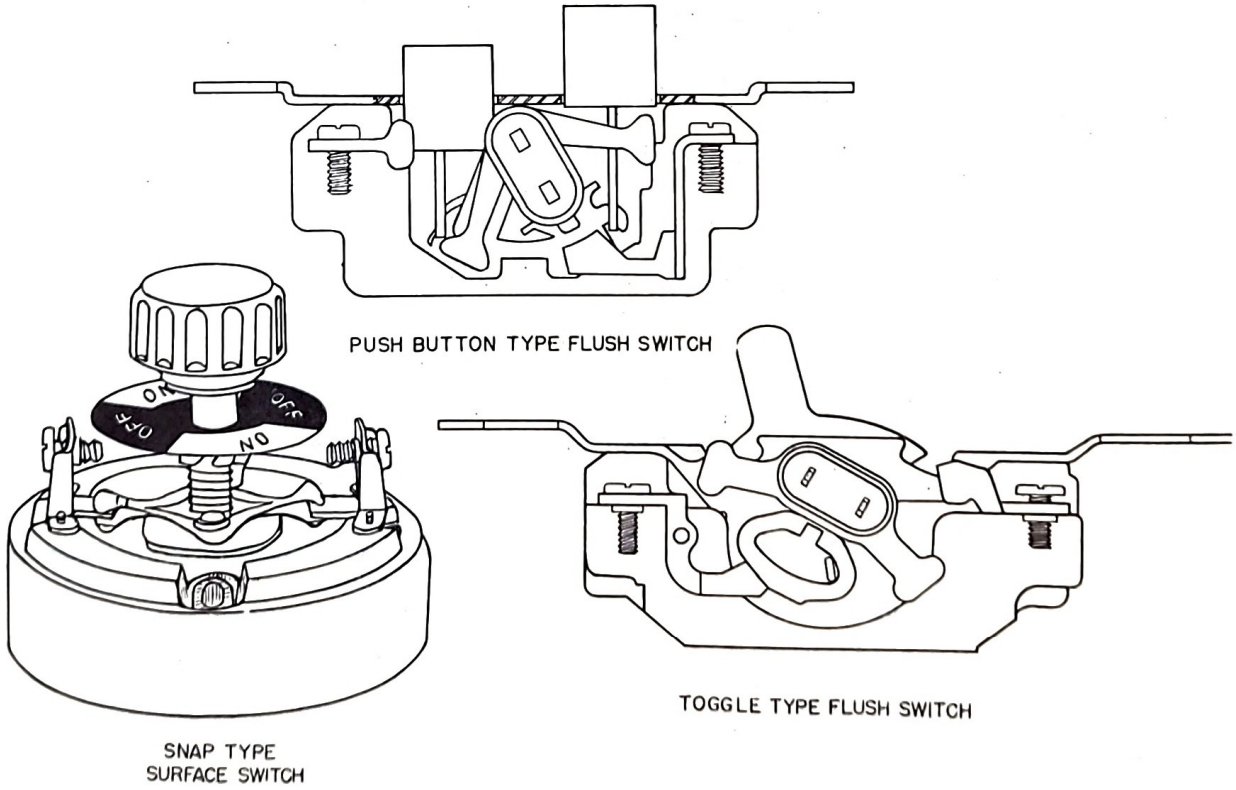


Fig. 52 Surface and flush mounted switches

A three-way switch has three terminals and one or two blades, which make the connections shown in fig. 53a. One or more lamps may be controlled from two locations by means of two three-way switches (fig. 53b). This scheme of wiring is frequently used for stairway lighting, as it makes it possible to control the lights from either the bottom or the top of the stairway.

If it is desired to control lights from more than two points, four-way switches must be connected between three-way switches. Four-way switches have four terminals and two blades, which make the connections shown in fig. 53c. The method of connecting switches to control lamps from four points is shown in fig. 53d.

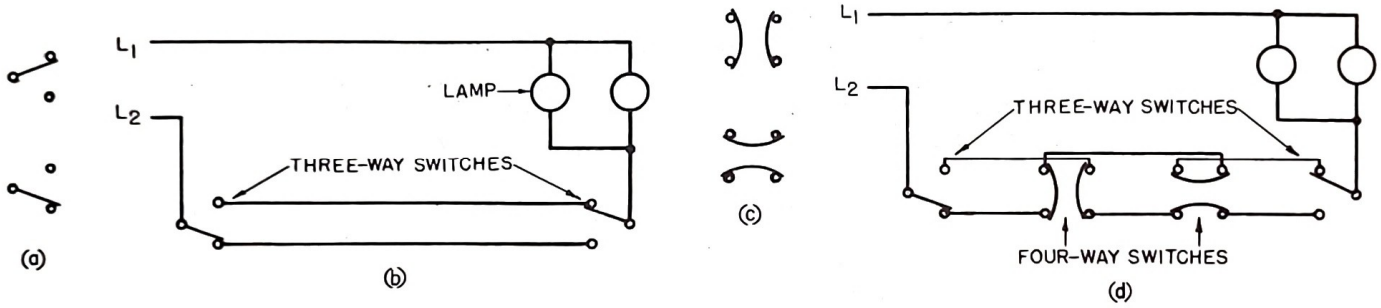


Fig. 53 Method of connecting three-way and four-way switches

HOME WORK

1. (a) What is the internal diameter of half inch electric metallic tubing? (b) One inch electric metallic tubing?

2. For what use is electric metallic tubing prohibited?

3. What are the chief uses of flexible conduit?

4. What is the difference between BX and BXL?

5. Give the industrial applications of armored cable and non-metallic sheathed cable.

6. How are armored cable and non-metallic sheathed cable installed (a) in the direction of the joists, and (b) at right angles to the joists?

7. Describe two methods of connecting non-metallic sheathed cable to boxes.

8. (a) For what use is non-metallic sheathed cable prohibited? (b) For what use is surface metal raceway prohibited?

9. Why is surface metal raceway more suitable for exposed work than other materials?

10. Give the uses of (a) rubber covered wire, (b) varnished cambric covered wire, and (c) asbestos covered wire.

11. Give the uses of flexible cord.

12. What is the difference between type SJ and type S cord?

13. By means of a diagram, show how a lamp is controlled from three switches.

The importance of a thorough understanding of magnetism cannot be over-estimated, for it is involved in the operation of practically all kinds of electrical apparatus, such as dynamos, transformers, indicating instruments, and lifting magnets.

Magnets may be divided into three classes--natural, artificial, and electro-magnets.

NATURAL MAGNETS.- Long before the Christian era it was discovered that certain iron ore possessed the peculiar property of being able to attract small pieces of iron, steel, and a few other metals. It was later discovered that an elongated piece of this ore would assume a nearly north and south position if freely suspended. For that reason it was used as a compass and called lodestone, which means leading stone.

ARTIFICIAL MAGNETS.- The natural magnets described above no longer have any practical value, the various types of magnets now in commercial use being made artificially from iron or steel. A piece of iron or steel may be magnetized by rubbing it with a magnet, but a better method is to magnetize it with an electric current. A practical way to magnetize a steel bar, for instance, is to insert the bar in a coil of insulated wire and then pass a heavy direct current through the coil. If the bar is made of hardened steel, it will be difficult to magnetize, but when once magnetized, it will retain indefinitely a large percentage of its magnetic strength. If the bar is made of soft steel or iron, it will be easy to magnetize, but when the magnetizing force is removed, most of the magnetism will soon disappear. The magnetism that remains after the magnetizing force has been removed is called residual magnetism.

FIELD ABOUT A BAR MAGNET.- If a piece of cardboard is placed over a bar magnet and iron filings sprinkled over the cardboard, the filings will arrange themselves as shown in fig. 1. The arrangement of the filings will be more pronounced if the cardboard is tapped gently as the filings are sprinkled.

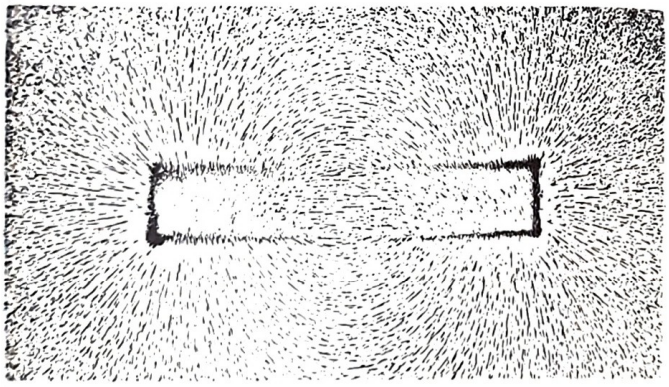


Fig. 1 Field of bar magnet indicated with iron filings

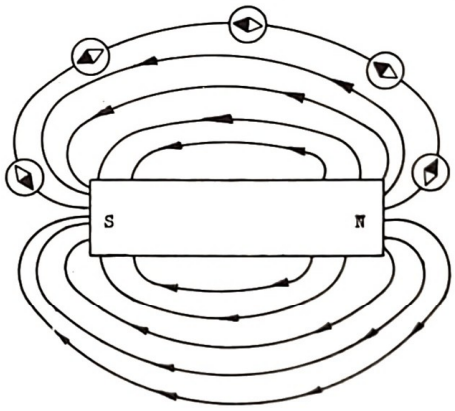


Fig. 2 Field of bar magnet indicated with a compass

DIRECTION OF MAGNETIC FIELD.- Fig. 1 shows that magnetism manifests itself as if it existed in lines, and for that reason we speak of lines of magnetism or magnetic lines. The space through which these lines pass is called the magnetic field. If a small compass is placed in various parts of a magnetic field, it will be found that the magnetic lines have a definite direction. The lines seem to emanate from one end of the magnet, flow through the air to the opposite end, and return through the magnet itself, as shown in fig. 2. The two ends of the magnet are called the poles. These poles are distinguished by the position they take when they are suspended freely. The end which points toward the north pole is called the north-seeking pole or simply the north pole, and the other is called the south-seeking or south pole.

In practice it is desirable to assume that the magnetic lines leave the magnet at the north pole and reenter at the south pole. Within the magnet the lines continue from the south pole to the north pole. Thus each line forms a closed loop.

BREAKING A MAGNET.- As just explained, a magnetic bar has two poles. If a magnetized bar is broken into a number of pieces, as shown in fig. 3, each piece will constitute a bar magnet with its north and south poles in the same respective directions as those of the original magnet. The reason for this will be evident if it is observed that the magnetic lines still continue to pass from one piece to the next, and in so doing, constitute a north pole where the magnetism leaves a piece and a south pole where the magnetism enters a piece.

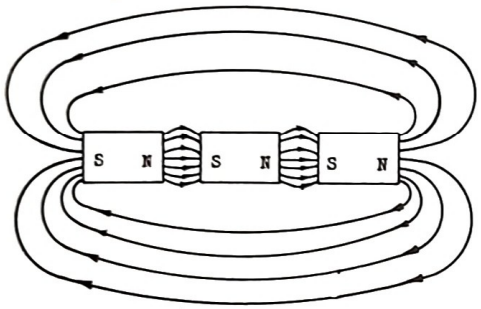


Fig. 3
Field through broken bar magnet

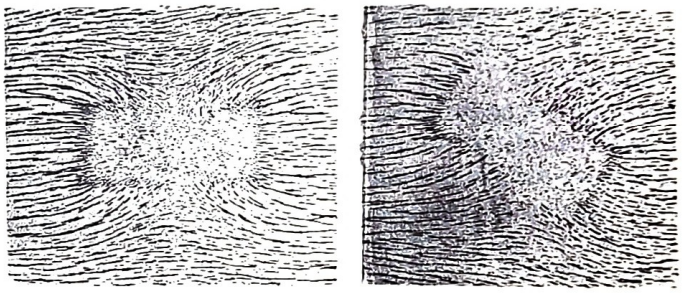


Fig. 4
Lines crowding into a piece of iron

PROPERTIES OF MAGNETIC LINES.- Magnetic lines have certain properties that should be clearly understood in order to understand what comes later.

1. There is no insulator for magnetic lines; they pass through all materials.
2. Magnetic lines pass easily through materials that can be magnetized. As shown in fig. 4, when a piece of iron is placed in a magnetic field, the lines crowd into the iron instead of passing through the air.
3. Magnetic lines tend to shorten as though they were stretched rubber bands. For this reason they are sometimes called lines of force.
4. Two magnetic lines that extend in the same direction tend to push each other apart.

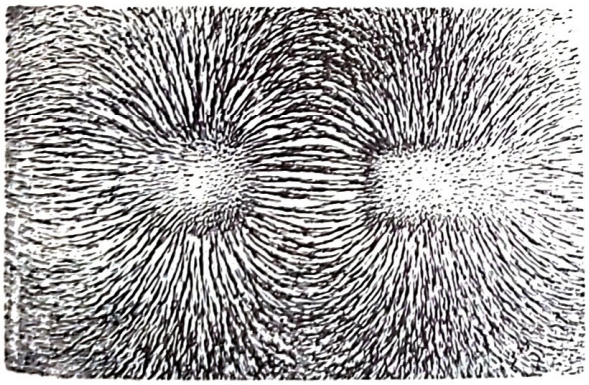


Fig. 5 Magnetic field
between two unlike poles

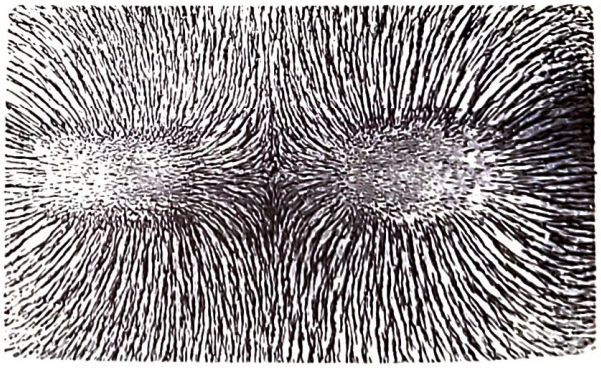


Fig. 6 Magnetic field
between two like poles

ATTRACTION AND REPULSION.- If the north pole of a magnet is placed near the south pole of another magnet, there will be a mutual attraction between the poles. The cause for this attraction is evident from fig. 5. The magnetic lines leave the N pole and enter the S pole. Since these lines are under tension, like rubber bands, they tend to shorten and to pull the two poles together.

The rule, then, for magnetic attraction and repulsion is as follows: Unlike magnetic poles mutually attract each other, while like magnetic poles mutually repel each other.

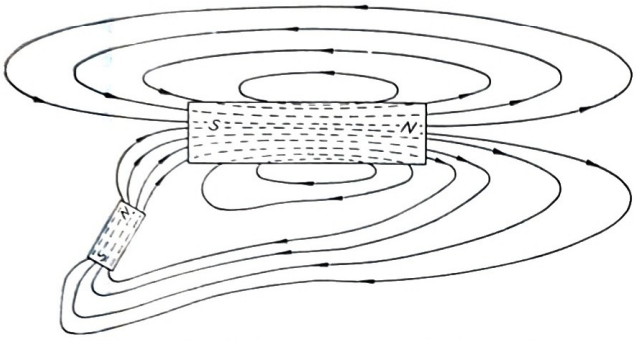


Fig. 7 Attraction of iron by a magnet.

IRON ATTRACTED BY A MAGNET.- Since magnetism passes more readily through iron or steel than through air, these materials are attracted by a magnet. For instance, when a piece of soft iron is placed near a magnet (fig. 7), the field is distorted by the lines tending to pass through the iron instead of through the air, because the iron offers an easier path. The iron now has a north and a south pole of its own, since magnetic lines enter one end and leave the other. As a result there will be two magnets with their unlike poles near each other; therefore attraction occurs.

WEBER'S THEORY.- The above phenomena regarding magnetism are explained by Weber's theory as follows: Matter is made up of small particles called molecules. There seems to be good evidence that each molecule is a magnet with a north and a south pole. In iron and steel these molecular magnets are comparatively strong, while in most other materials they are very weak.

In an unmagnetized bar they are arranged in a haphazard manner, as shown in fig. 8a, so that the various north and south poles all neutralize one another and no external magnetic effect is produced. Upon bringing a magnetizing force, such as a permanent magnet near one end of the unmagnetized bar, the little magnets tend to line up with their axes parallel (fig. 8b). This is due to the laws of magnetic attraction and repulsion. The north poles will all point in one direction, and the south poles will all point in the opposite direction. The bar will have become magnetized and will produce an external magnetic field. This also explains why breaking a magnet into several pieces (fig. 8c) leaves perfect magnets, each having a north and a south pole.

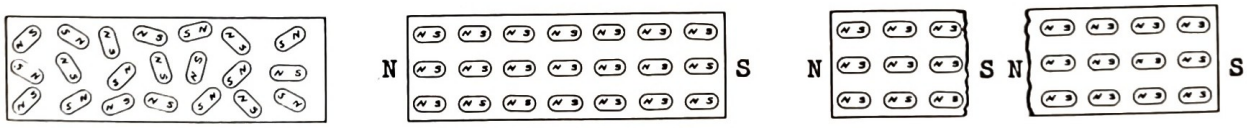


Fig. 8 The arrangement of molecules in a bar.

The reason that steel is hard to magnetize is that there is a high frictional resistance between the molecules, making it difficult to swing them around so that their axes are parallel. However, once parallel, they are equally difficult to get out of line; therefore, steel retains its magnetism well.

Soft iron is easily magnetized because there is a low frictional resistance between the molecules, making it easy to swing them into line. However, when the magnetizing force is removed, the molecules tend to lose their alignment; therefore, soft iron does not retain its magnetism very well. Hence, steel is always used where permanent magnets are desired.

INTERMEDIATE POLES.- Usually a magnet has only two poles, but it is possible to magnetize a bar so that it will have more than two poles. Fig. 9 shows one method of securing such a magnet. The bar is placed, so that each end rests on a north pole, and is stroked at the middle with the south pole of a third magnet. The bar will then be found to be magnetized with a south pole at each end and a north pole in the middle.

It is evident that in this case we have in reality two magnets with the two north poles at the middle. Such an intermediate pole is frequently produced on iron and steel bars that have been in contact with lifting magnets.

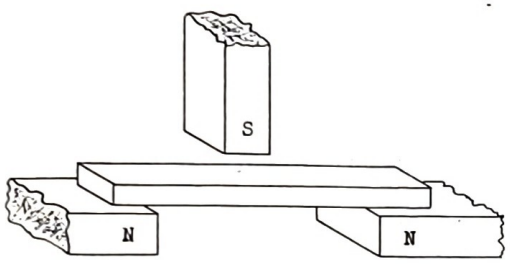


Fig. 9 Method of magnetizing a bar with an intermediate pole.

MAGNETIC SCREENS.- There is no known substance that will insulate against magnetic flux. A magnetic field readily passes through any such substances as glass, copper, wood, etc. Because of this fact, it is sometimes difficult to eliminate the effect which stray magnetic fields have upon electric measuring instruments. For instance, a conductor carrying a large current produces a strong magnetic field, which may affect meters in the vicinity. The meters are therefore shielded by placing them in a cast iron case (fig. 10) so that the stray lines of force take the path through the case and do not influence the meters.

Expensive watches carried in electric power plants should be kept in soft iron cases to protect the steel parts from becoming magnetized, for a magnetized watch either looses or gains time.

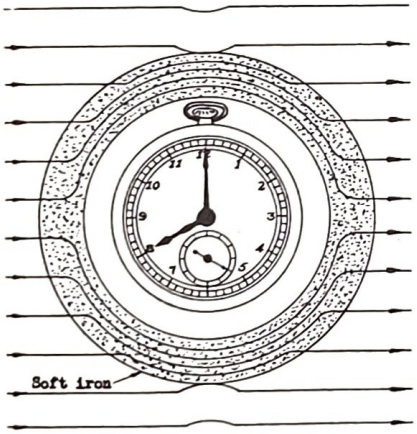
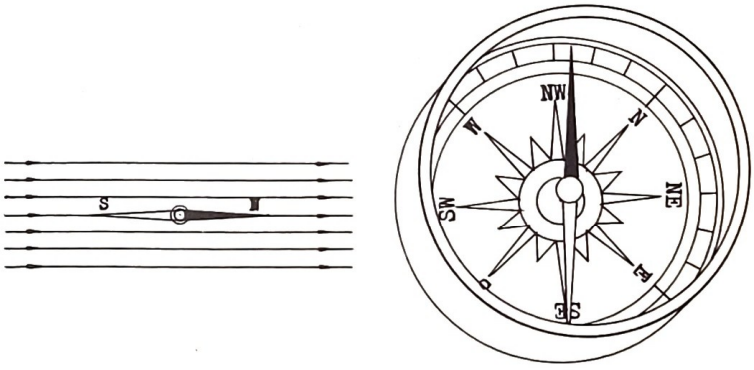


Fig. 10 Instrument shielded by a magnetic screen.



(a) (b)

Fig. 11 A compass.

THE COMPASS.- A compass is merely a thin bar magnet, accurately balanced and suspended on a pivot so that it may rotate freely. This thin bar, which is usually called a needle, always tends to set itself in the direction of the magnetic field in which it is placed, the north end, which is usually colored blue, pointing in the direction of the magnetic lines. This is illustrated in fig. 11a.

A compass of the type shown in fig. 11b in much used in practice. It enables one to determine whether or not a material is magnetized and to determine the polarity of poles in a dynamo, which in turn indicates whether or not the field coils have been connected correctly. It also enables one to find faults in armatures of D.C. and A.C. machines.

THE EARTH'S MAGNETIC FIELD.- It has been known for a long time that the earth is a huge magnet, whose two poles coincide approximately with the geographical poles. Magnetic lines of force emanate from the magnetic north pole, proceed to the magnetic south pole, and return to the magnetic north pole through the earth. Thus, the space in which we live is permeated with magnetic lines, which ordinarily occupy roughly a north and south position. It is this magnetic field that causes a compass at the earth's surface to point toward the north.

In 1819, Oersted, a Danish physicist, made a discovery which aroused a great deal of interest because it showed the first evidence of a connection between magnetism and electricity. He found that an electric current is always accompanied by certain magnetic effects and that these effects obey certain definite laws. These important laws may be demonstrated by sending a large current through a vertical wire which passes through a horizontal piece of cardboard. A magnetic effect will be produced, which may be observed by sprinkling iron filings on the cardboard while it is being gently tapped. It will be seen that the filings arrange themselves in concentric rings about the wire. An examination of the filings will show that each magnetic line forms a complete circle by itself. By placing small compasses at various positions on the cardboard (fig. 12), one may see that the needles always point in a direction parallel to the circular magnetic lines. When the current flows through the wire as indicated, the needles will point in a counter-clockwise direction. If the current is reversed, the needles will point in a clockwise direction. Evidently the direction of the lines depends upon the direction of the current through the conductor.

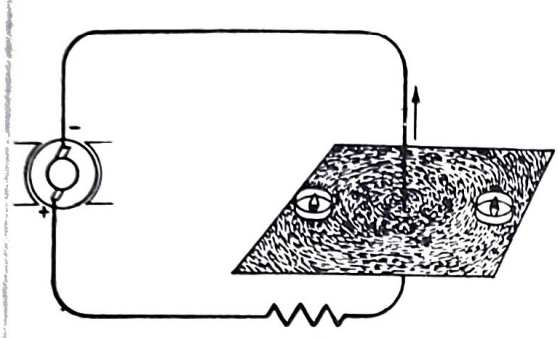
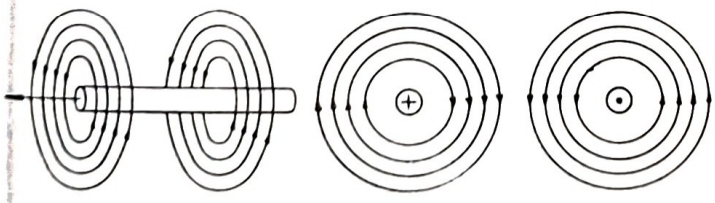


Fig. 12 Iron filings and compasses showing shape and direction of the magnetic field around a conductor

Fig. 13a shows a section of a current-carrying wire with its magnetic field, while figs. 13b and 13c show cross sections of this wire. In fig. 13b note that the direction of the current is away from the observer, and that the magnetic lines are clockwise. In fig. 13c the field about the same wire is shown with the current reversed. Note that the direction of the current is toward the reader and that the lines extend counter-clockwise. A convenient rule for remembering the relation that exists between the magnetic lines around a conductor and the direction of current through the conductor is as follows:

THUMB RULE.- If the conductor is grasped in the right hand with the thumb pointing in the direction of the current, the fingers will point in the direction of the magnetic field.

Thus, if the direction of current is known, the direction of the lines can be readily determined; or conversely, if the direction of the lines is known, the direction of the current can be readily obtained. The thumb rule is illustrated in fig. 14.



(a) (b) (c)

Fig. 13 Magnetic field about a straight wire carrying a current

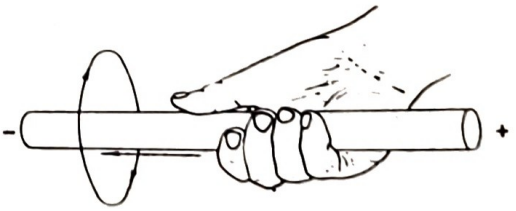
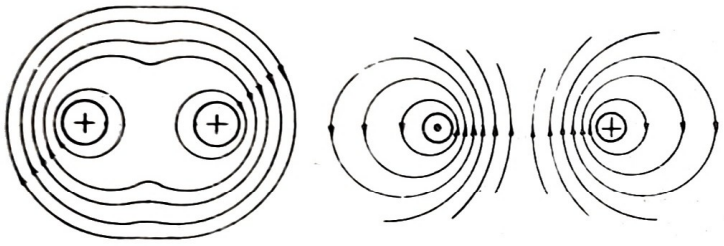


Fig. 14
Right-hand thumb rule

MAGNETIC FIELD ABOUT TWO PARALLEL CONDUCTORS.- When two parallel conductors carry current in the same direction, the magnetic fields tend to draw them together (see fig. 15a, which shows the cross section of two parallel wires with the currents flowing away from the observer). The magnetic lines between the conductors neutralize, producing the field shown in fig. 15a. Since magnetic lines tend to contract, the conductors will be forced toward each other.

Fig. 15b shows parallel conductors with currents in opposite directions. Since the lines around one conductor are opposite in direction to those around the other, the two magnetic fields will not join as in fig. 15a, nor cross, but there will be a lateral crowding effect that tends to push the conductors apart. Under short-circuit conditions, bus bars have been torn loose from their supports by the powerful magnetic action of parallel currents.



(a) (b)

Fig. 15
Magnetic fields about two parallel conductors

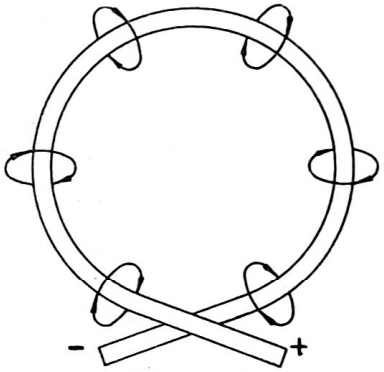


Fig. 16
Lines of force around a single turn of wire carrying current

If we apply the thumb rule to a wire bent into a loop as shown in fig. 16, we find that the lines of force which encircle the conductor will enter the same face of the loop and come out at the other face.

If several loops are placed together in a loose coil as shown in fig. 17, most of the lines will thread the whole coil and return on the outside of the coil to the other end. The reason that practically no magnetic lines encircle the loops of a closely wound coil, but thread the entire coil, can be seen by studying fig. 18, which is an enlarged cross section of fig. 17. The current enters at A, B, and C and comes out at D, E, and F. If A and B are sufficiently near each other, the field on the right side of A will neutralize the field on the left side of B, since the fluxes are in opposite directions. The same can be said about the fluxes between any two adjacent turns. Thus the magnetic lines are compelled to continue through the whole length of the coil and cannot pass between the turns. This produces the same shape of field that is found about a bar magnet, the end from which the lines come out being a north pole and the end in which the lines enter being a south pole.

Magnetic field set up by a coil

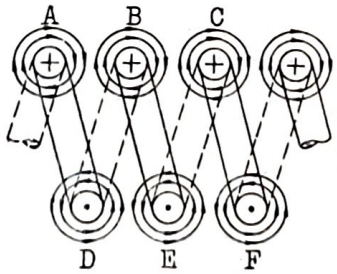


Fig. 18 Cross section of the coil in fig. 17

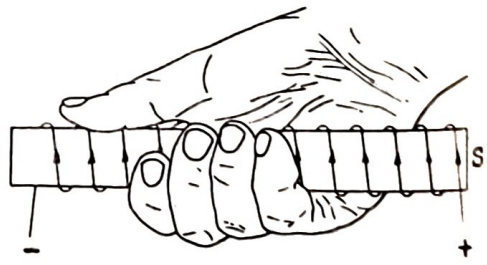


Fig. 19 Rule for polarity of a coil carrying current

THUMB RULE FOR COIL.- The relation between the direction of current and direction of magnetic flux may be conveniently expressed by the thumb rule as follows:

Grasp the coil with the right hand so that the fingers point in the direction of the current in the coil. Then the thumb extended longitudinally will point in the direction of the flux, or toward the north pole (fig. 19).

Thus the polarity may be determined if the direction of the current is known, and conversely, the direction of the current may be determined if the polarity is known.

A clear understanding of the operating characteristics of electrical machinery and auxiliary equipment requires a knowledge of the basic laws of magnetism as well as a knowledge of electricity. Fortunately, the laws of magnetic circuits are similar to those of electric circuits. Hence, instead of having to become familiar with new fundamentals, it is only necessary to become familiar with the fundamentals and laws of the electric circuit restated for magnetic circuits. To show how this is done, a simple magnetic circuit will be considered (fig. 20). This consists of a coil with a circular air core. When a current is sent through this coil as indicated, a magnetic flux is set up in a clockwise direction. The amount of flux is expressed in magnetic lines, just as the amount of electric current is expressed in amperes.

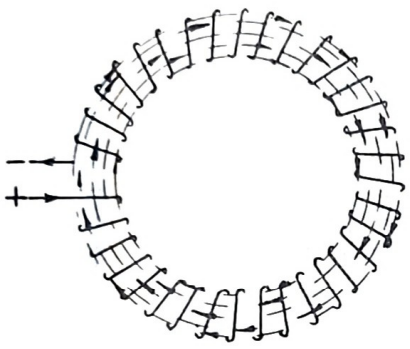


Fig. 20
A simple magnetic circuit

This flux is set up by a magnetomotive force (abbreviated m m f) produced by the coil carrying current, just as the current in an electric circuit is set up by an electromotive force produced by a battery. The number of magnetic lines actually set up is proportional to only two factors--the current flowing through the coil and the number of turns in the coil. Thus the m m f is expressed in a unit called the ampere-turn.

The number of ampere-turns (IN) is found by multiplying the number of turns by the current through them. For instance, a 300 turn coil carrying 2 amperes produces a m m f of 300 × 2 or 600 ampere-turns. The same m m f could be produced by a 100 turn coil carrying 6 amperes.

All magnetic circuits, including the one shown in fig. 20, offer resistance to the flow of magnetic lines. This magnetic resistance, called reluctance, is represented by the scrip letter $\mathcal{R}$ and is measured in a unit called the rel.

OHM'S LAW FOR MAGNETIC CIRCUITS.- The above shows that magnetic circuits are similar to electric circuits. There is a m m f which sets up a flux in the magnetic circuit, and a magnetic resistance, called reluctance, which opposes the flow of these lines. Then we may write a law for magnetic circuits which resembles Ohm's law for electric circuits.

Ohm's law for electric circuits is expressed as follows:

$$\text{Current} = \frac{\text{e m f}}{\text{Resistance}}, \text{ or Amperes} = \frac{\text{Volts}}{\text{Ohms}}, \text{ or in symbols } I = \frac{E}{R} \qquad (1)$$

Then for a magnetic circuit, Ohm's law may be expressed as follows:

$$\text{Flux} = \frac{\text{m m f}}{\text{Reluctance}}, \text{ or magnetic lines} = \frac{\text{Ampere-turns}}{\text{Rels}}, \text{ or in symbols } \Phi = \frac{IN}{\mathcal{R}} \qquad (2)$$

Equation 2 has as broad an application in magnetic circuits as equation 1 has in electric circuits.

EXAMPLE.- In fig. 12 the reluctance of the magnetic circuit is 2 rels, and the coil consists of 1000 turns of wire which carry 10 amperes. Determine the number of magnetic lines set up.

From equation 2, $\Phi = \frac{10 \times 1000}{2} = 5000$ lines

RELUCTANCE.- The reluctance of a magnetic circuit is determined in a manner similar to that used in determining the resistance of a conductor. A conductor's resistance is determined by substituting in the equation

$$R = \frac{K\,l}{(m)}$$

where K is the resistance of a unit piece (see lesson 12).

Similarly, the reluctance of a magnetic circuit may be determined if the reluctance of a unit piece is known. Since magnetic circuits are usually rectangular in cross section, it is convenient to use a one inch cube as a unit piece. The reluctance of an inch cube of a material is called the reluctivity, and is represented by the Greek letter ν (pronounced nu). Then the reluctance of a magnetic circuit may be found by multiplying the reluctivity ν by the length l, and dividing by the cross-sectional area A. Thus

$$\mathcal{R} = \frac{\nu\,l}{A} \qquad (3)$$

The value of K in an electric circuit does not change, regardless of how much current is flowing through the conductor, provided the temperature is kept constant. (For instance, the value of K for drawn copper is 10.7.) Likewise, the value of in non-magnetic materials does not change, regardless of how many magnetic lines there are flowing through the circuit. (Its value for air and all non-magnetic materials is .313.) Then the reluctance of non-magnetic materials may be found by the equation

$$\mathcal{R} = \frac{.313\,l}{A} \qquad (4)$$

EXAMPLE.- Compute the reluctance of a wooden ring 4 square inches in cross section, with an average diameter of 6 inches.

The length of the ring (πD) = 3.1416 × 6 = 18.8496 inches. Substituting in equation 4,

$$\mathcal{R} = \frac{.313 \times 18.8496}{4} = 1.475 \text{ rels}$$

HOME WORK

1. Determine the m m f produced by a coil of A turns carrying .5 ampere.
2. How much current must flow through a coil of B turns to set up 1,000,000 lines in a magnetic circuit having a reluctance of .007 rel?
3. What is the reluctance of a magnetic circuit in which a magnetomotive force of C ampere-turns sets up 200,000 lines?
4. A magnetic circuit similar to that of fig. 20 is 10 square inches in cross section and has an average length of 30 inches. Calculate the total flux produced if it has a reluctance of .8 rel and is energized with a 500 turn coil carrying D amperes.
5. An 1800 turn coil on a .9 rel magnetic circuit has 55 ohms resistance and is connected to an E volt supply. Find the amount of flux produced.
6. How many turns of wire carrying 10 amperes must be wound on a brass ring 4 square inches in cross section and 24 inches long to set up F magnetic lines?

PERMEABILITY.- The reluctivity of magnetic materials ranges from .007 to .00009, which is much less than the reluctivity of non-magnetic materials. To avoid dealing with small decimals, the term permeability is used, which is merely the reciprocal of reluctivity. Permeability is denoted by μ, a Greek letter pronounced mu. Thus

$$\mu = \frac{1}{\nu}$$

Since the reluctivity for non-magnetic materials is .313, their permeability is 1/.313 or 3.19.

The permeability or reluctivity of a magnetic material cannot be stated, even if its composition and heat treatment are known, because the flux does not change in direct proportion to the magnetizing force (ampere-turns). To make this clear, suppose we consider a steel ring surrounded by a coil. As the magnetizing force is gradually increased from zero to large values, the flux density increases as indicated by the magnetization curve B in fig. 21. It should be noted that the flux density increases slowly at first, but soon rises rapidly until at high values of magnetizing force it again increases only gradually. From this illustration we must conclude that the permeability of iron and steel depends upon the number of magnetic lines flowing in the material. It is not constant, varying with the flux density in the manner indicated by curve μ.

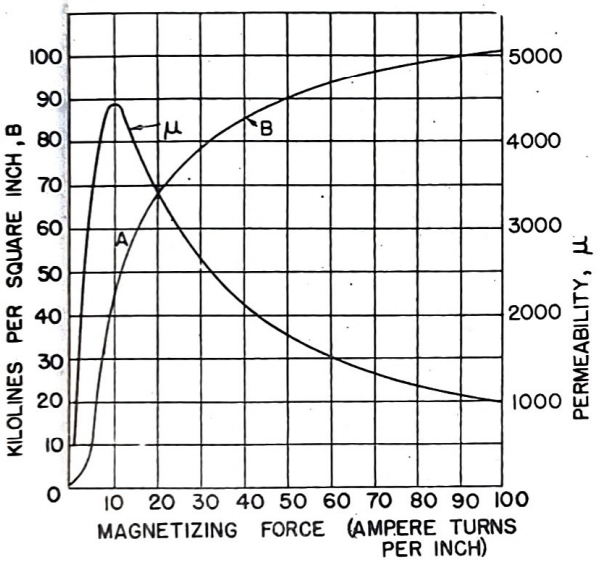


Fig. 21 Magnetization and permeability curve

Note that to about point A the m m f is very effective in producing flux, but beyond this point it must be increased tremendously to cause the flux density to increase slightly. In magnetic circuits it is not practical to use a flux density above point A, because too many ampere-turns are required to produce the added flux. Point A, commonly called the saturation point, is not a point at which the magnetic material contains so many lines that no more can be added, but the point beyond which it is uneconomical to add more lines.

Thus a constant cannot be used for the permeability of magnetic materials, as in non-magnetic materials. However, curves may be used to show the permeability corresponding to different flux densities.

FLUX DENSITY.- The number of lines per square inch is called the flux density and is denoted by B. The flux density B may be found by dividing the total flux by the cross-sectional area of the magnetic circuit A. Thus

$$B = \frac{\Phi}{A} \qquad (5)$$

The magnetizing force required per inch of a magnetic circuit is denoted by H, and depends only upon flux density and permeability. This may be proved as follows.

$$\Phi = \frac{IN}{\mathcal{R}} \qquad (6)$$

But $\Phi = BA$, $IN = Hl$, and $\mathcal{R} = \frac{l}{\mu A}$ (7)

Then substituting for Φ, IN, and $\mathcal{R}$ in equation 6 gives

$$BA = \frac{Hl}{\frac{l}{\mu A}} \text{ or } H = \frac{B}{\mu} \qquad (8)$$

Thus to determine the ampere-turns per inch of magnetic circuit, it is only necessary to know the flux density and permeability. Then instead of using curves which give the permeability corresponding to different flux densities, as suggested above, equation 8 makes it possible to plot curves giving the direct relation between flux density B and ampere-turns required per inch H. Fig. 22 shows such curves, which save considerable calculation, because instead of determining the ampere-turns by finding the reluctance and multiplying it by the flux, we find the ampere-turns per inch directly from the curves, and multiply by the length of the magnetic circuit.

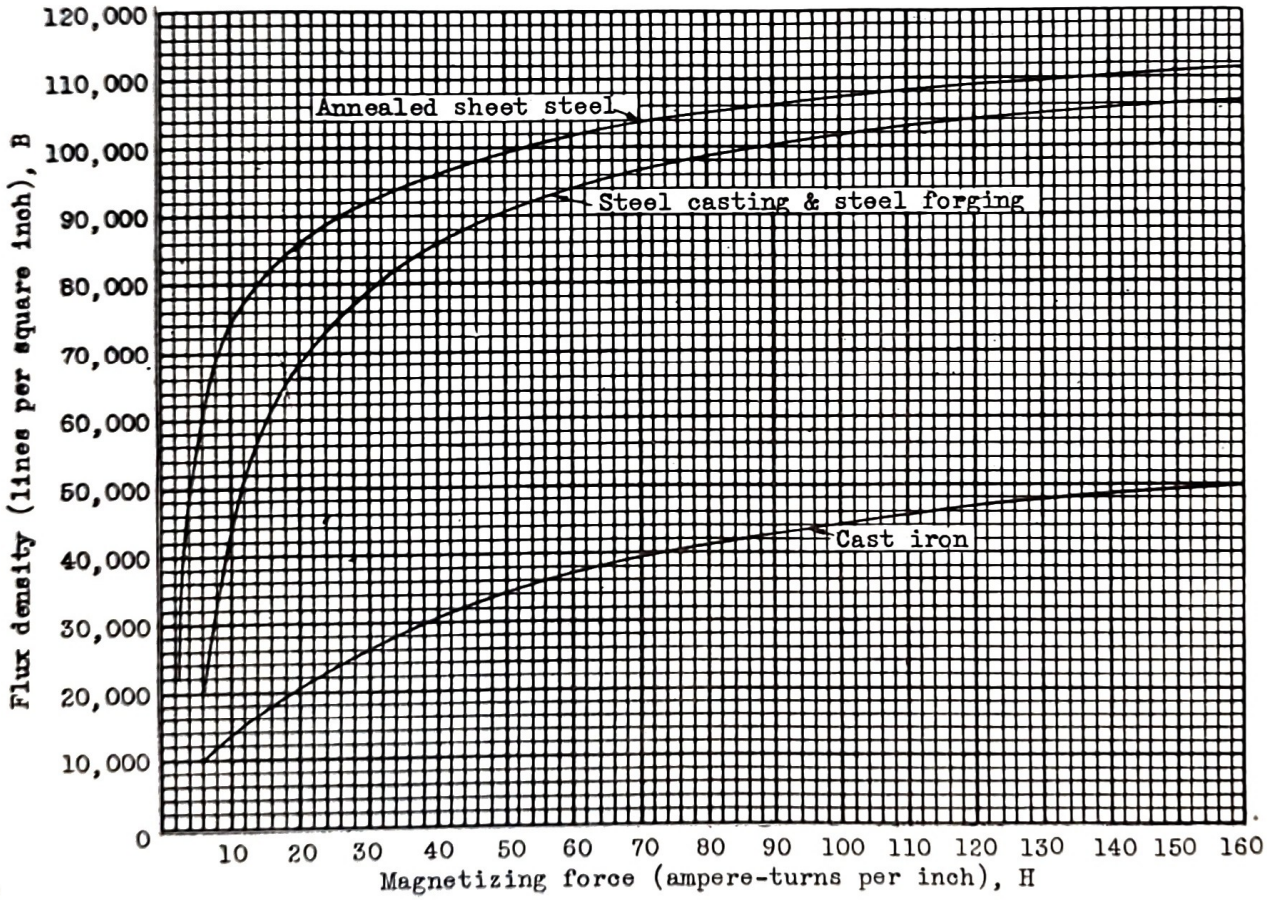


Fig. 22 Magnetization curves of commercial iron and steel

In problems arising in practice, it is usually necessary to compute the number of ampere-turns required to produce a certain flux. To show how this is accomplished with the aid of the curves of fig. 22, the following example will be considered.

EXAMPLE.- The magnetic circuit of fig. 23 is made of cast iron and the coil contains 300 turns. Determine the current required to set up 100,000 magnetic lines.

The flux density $B = \frac{100,000}{4} = 25,000$ lines per square inch.

For this flux density, the curve for cast iron shows that 28 ampere-turns per inch are needed. Then the required number of ampere-turns is 28 × 16 or 448.

Since the coil has 300 turns,

$$I = \frac{448}{300} = 1.49 \text{ amps}$$

Occasionally it is necessary to determine the permeability of certain materials at some specific flux density. The method of doing this is illustrated by an example.

EXAMPLE.- Determine the permeability of annealed sheet steel at a flux density of 80,000 magnetic lines.

At 80,000 lines sheet steel requires 14 ampere-turns per inch (see fig. 22).

Substituting in equation 6 and solving for μ,

$$\mu = \frac{80,000}{14} = 5714.3$$

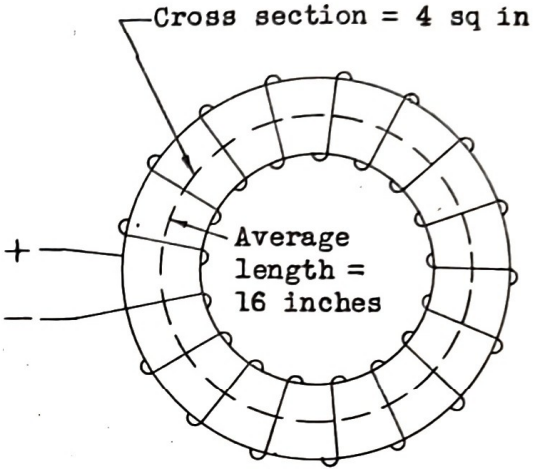


Fig. 23
Simple magnetic circuit

Magnetic circuits may be joined in series or in parallel. Problems involving either of these cases may be solved by methods that are similar to those used in corresponding electric circuits.

SERIES MAGNETIC CIRCUITS.- In a series circuit the number of magnetic lines through all sections is the same, though the flux density may be different. If a series circuit is made up of different kinds of iron, contains air gaps, or is made up of parts that have different flux densities, the total m m f required is found by adding the ampere-turns of the separate parts.

The m m f required for an air gap or a piece of non-magnetic material may be determined by a simple equation, developed as follows:

$$\Phi = \frac{IN}{\mathcal{R}}$$

Substituting BA for Φ and $\frac{.313l}{A}$ for $\mathcal{R}$, we have the following equation:

$$BA = \frac{IN}{\frac{.313l}{A}}$$

Solving for IN, $$IN = .313Bl \qquad (9)$$

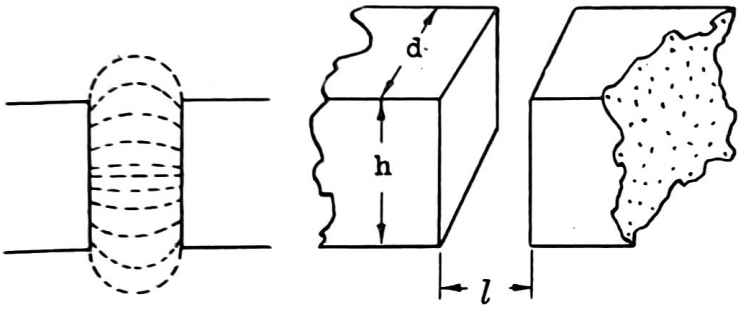
The flux density in an air gap is very difficult to compute accurately, because the magnetic lines spread out on passing through the air, as indicated in fig. 24a. If an air gap is exceedingly short (not more than 3/16 of an inch), we may assume that it has the same flux density as the iron. Otherwise, it is a good approximation to assume that the flux fringes outward on each side for a distance equal to the length of the air gap. With this assumption the cross-sectional area of the air gap shown in fig. 24b may be determined by the following equation:

$$A = (h + l)(d + l) \qquad (10)$$

EXAMPLE.- Determine the number of ampere-turns required to set up 210,000 magnetic lines through the circuit shown in fig. 25.

In part X the flux density $B_X = \frac{210,000}{3} = 70,000$ magnetic lines per square inch

The ampere-turns per inch required for a density of 70,000 lines per square inch in steel casting is 21.5. For this part, 21.5 × 14 or 301 ampere-turns are required.



(a) (b)

Fig. 24 Flux fringing in an air gap

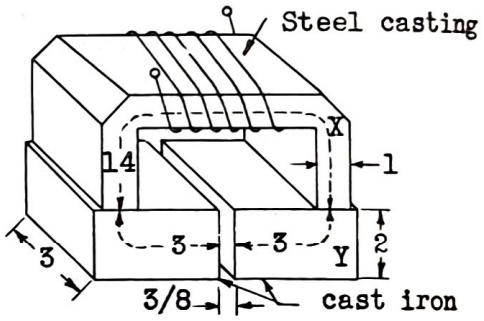


Fig. 25
Series magnetic circuit

In part Y the flux density $B_Y = \frac{210,000}{6} = 35,000$ magnetic lines per square inch

The m m f per inch required for a density of 35,000 lines in cast iron is 53 ampere-turns. For the two cast iron parts, 54 × 6 or 324 ampere-turns are required.

According to equation 10, the air gap area $A = (2 + \frac{3}{8})(3 + \frac{3}{8})$ or 8 square inches.

The flux density $B = \frac{210,000}{8}$ or 26,250 lines per square inch.

By equation 9, $IN_a = .313 \times 26,250 \times .375 = 3081$ ampere-turns.

The total number of ampere-turns required is 301 + 324 + 3081 = 3705.

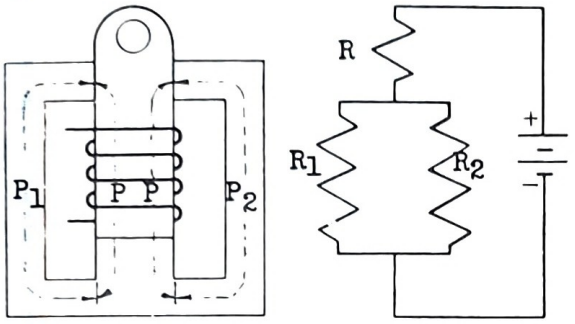
More than 80 per cent of the total m m f is required to force the flux through the air gap. This is because the reluctance of the air gap is much greater than that of the iron. To use the smallest number of ampere-turns on a magnetic circuit, the air gap should be made as small as possible.

HOME WORK

1. A magnetizing force of A ampere-turns per inch produces what flux density in cast iron? In cast steel? Determine the permeability of these materials with this magnetizing force.
2. A cast steel circuit 12 square inches in cross section is to carry B magnetic lines. Determine the magnetizing force required per inch.
3. How many ampere-turns are necessary to force C magnetic lines through a cast steel circuit 3 square inches in cross section and 9 inches long?
4. Determine the number of ampere-turns required to set up D magnetic lines in the magnetic circuit of fig. 25 if parts X and Y are both annealed sheet steel.
5. A ring of steel casting has an average circumference, not including a .5 inch air gap, of E inches. Calculate the number of ampere-turns required to set up 60,000 lines per square inch.

PARALLEL MAGNETIC CIRCUITS.- In practice magnetic circuits are frequently in parallel. The flow of magnetism through parallel circuits is governed by the same laws as the flow of current through electric circuits.

When studying electric circuits, we learned that the e m f that forces current through one path also forces the currents through all the other parallel paths. A similar law also applies to parallel magnetic circuits; that is, the m m f that forces flux through one path also forces the flux through all the other parallel paths.



(a) (b)

Fig. 26 Parallel magnetic circuit and corresponding electrical analogy

Fig. 26a shows the magnetic circuit of a plunger type of electromagnet. The magnetic lines on leaving the middle portion P divide equally and flow through the two portions P_1 and P_2, which have the same reluctance. Such a circuit is similar to the electric circuit of fig. 26b. In this circuit, resistance R carries the total current and corresponds to the portion P of the magnetic circuit. Resistances R_1 and R_2 are equal and in parallel; thus each carries half the current through R. Then R_1 and R_2 correspond to P_1 and P_2 of the magnetic circuit. The e m f necessary to force a current I through the electric circuit equals the e m f necessary to force I amperes through R plus the e m f necessary to force I/2 amperes through either R_1 or R_2.

Similarly, the m m f necessary to force Φ lines through the magnetic circuit equals the m m f necessary to force Φ lines through P plus the m m f necessary to force $\Phi/2$ lines through either P_1 or P_2.

EXAMPLE.- In fig. 26a the portion P is 4 square inches in cross section and 6 inches in length. The two portions P_1 and P_2 are each 2 square inches in cross section and 8.5 inches in length. If the entire magnetic circuit is a steel forging, determine the number of ampere-turns required to force 360,000 magnetic lines through P.

The flux density throughout the magnet $B = \frac{360,000}{4} = 90,000$ lines per square inch. For this density in a steel forging, 50 ampere-turns per inch are required. Then part P requires 50 × 6 or 300 ampere-turns, and part P_1 or P_2 requires 50 × 8.5 or 425 ampere-turns. The total m m f required is then 300 + 425 or 725 ampere-turns.

NUMBER OF TURNS AND SIZE OF WIRE.- After the number of ampere-turns for a magnetizing coil has been computed, it is at times necessary to determine the size of the wire and the number of turns that may be used to suit a given voltage. A suitable equation for determining the wire size may be developed as follows:

The resistance of the coil is $R = \frac{K l}{\text{(m)}}$ (11)

If l_t represents the average length per turn in inches, then $l = \frac{l_t N}{12}$

Substituting for l in equation 11, $R = \frac{K l_t N}{12\text{(m)}}$

According to Ohm's law, $R = \frac{E}{I}$

Then $\frac{E}{I} = \frac{K l_t N}{12 \text{ⓜ}}$.

Solving for ⓜ, we have $\text{ⓜ} = \frac{K l_t I N}{12E}$ (12)

Equation 12 is a suitable equation for determining the wire size. The current through a coil is fixed by the current-carrying capacity of the wire, which for air cooled coils is 1200 circular mils per ampere.

EXAMPLE.- In fig. 25, 3524 ampere-turns are required to set up the desired flux. If the magnetizing coil is connected to 12 volts and is one inch thick, determine the size of wire and the number of turns required.

Substituting in equation 12, $\text{ⓜ} = \frac{10.7 \times 12 \times 3524}{12 \times 12} = 3142.2$ circular mils.

(A number 15 wire will be used, which has a circular mil area of 3256.7.) Since 1200 circular mils are required per ampere, then

$$I = \frac{3256.7}{1200} = 2.7 \text{ amperes}$$

$$N = \frac{IN}{I} = \frac{3524}{2.7} = 1305 \text{ turns}$$

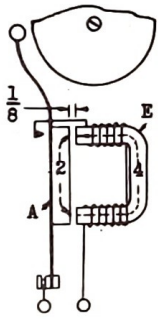


Fig 26 - 1

HOME WORK

1. The electromagnet E in fig. 26-1 is .25 sq in. in cross section and the armature A is A sq in. in cross section. Neglecting flux fringing at the air gap, determine the number of ampere-turns required to set up 20,000 lines through the circuit if both E and A are steel castings.

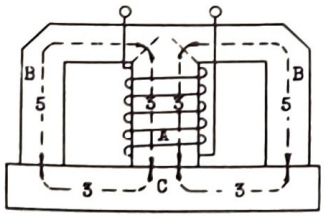


Fig. 26 - 2

2. In fig. 26-2 the electromagnet is of annealed sheet steel, portion A is 12 sq in. in cross section, and portions B are each 8 sq in. in cross section. Portion C is of cast iron 14 sq in. in cross section. If the coil has B turns, how much current must flow through it to set up 960,000 lines through A?
3. A magnetic circuit of a two pole generator is shown in fig. 26-3. The yoke is a steel casting 14 sq in. in cross section and the armature and field poles are of annealed sheet steel. One path through the armature is 12 sq in. in cross section and the field poles are each 26 sq in. in cross section. The air gap is C sq in. in cross section. Determine the number of ampere-turns necessary on each field pole to set up 2,000,000 lines in the air gap.

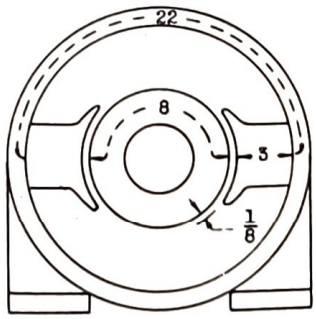


Fig. 26 - 3

4. Suppose that 4500 ampere-turns are required to set up the desired flux in a magnetic circuit that is 1 by 3 inches in cross section. If the coil on this magnetic circuit is 1 inch thick and is connected to a D volt supply, determine: (a) the size of wire required; (b) the current through the coil.

HYSTERESIS.- If a coil on an iron core is energized, a flux will be set up which will increase in the manner suggested by curve ab in fig. 27. A similar curve for a steel casting was shown in fig.22 of lesson 19 B, and called a saturation or magnetization curve.

When the current in the coil of fig. 27 is decreased, the flux density will not decrease along line ab, but will decrease less rapidly as indicated by line bc. The magnetizing force is zero when c is reached, but the flux density is 50,000 lines per square inch. This flux, which remains after the magnetizing force has been removed, is called residual magnetism. The reason it remains may be explained as follows.

The molecules of a magnetic material are small magnets haphazardly arranged. When a magnetizing force is applied, the little magnets tend to line up with their axes parallel. Their motion is resisted by molecular friction, however, which produces heat. When the magnetizing force is removed, forces of attraction and repulsion tend to turn the little magnets back to their normal position. As before, friction tends to resist this motion and additional heat is produced. This molecular friction also prevents the molecules from completely returning to their normal position. Thus the material is magnetized to some degree even after the magnetizing force is completely removed.

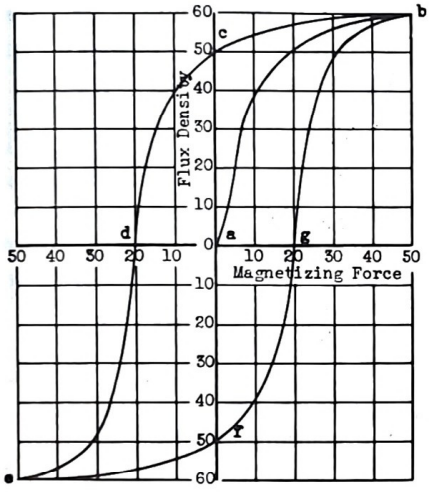


Fig. 27 A hysteresis loop

At d (fig. 27) the residual magnetism has been reduced to zero by reversing the coil current and producing a m m f of 20 ampere-turns per inch.

As this reversed coil current is increased further, the flux density will build up as indicated by curve de. For equal magnetization, the flux density at e is the same as at b.

If the coil current is reduced to zero, the flux density will decrease along the curve ef and will again reach 50,000 magnetic lines at zero magnetization.

To reduce the flux to zero, it is necessary to supply a magnetizing force ag equal to ad.

While increasing the magnetizing action to 50 ampere-turns per inch, the flux density will return to its first maximum value, which is at b. This closes the loop.

It is thus seen that the flux lags behind the magnetizing force, and this lagging effect is called hysteresis. In DC and AC machines the flux is continually changing in this way, and as a result some power is converted into heat.

INDUSTRIAL APPLICATIONS.- A group of industrial applications of magnetism which may be discussed conveniently at this time are lifting magnets, magnetic chucks, magnetic clutches, magnetic brakes, and magnetic separator pulleys.

LIFTING MAGNETS.- Lifting magnets are often used to transfer large amounts of iron and steel from one place to another.

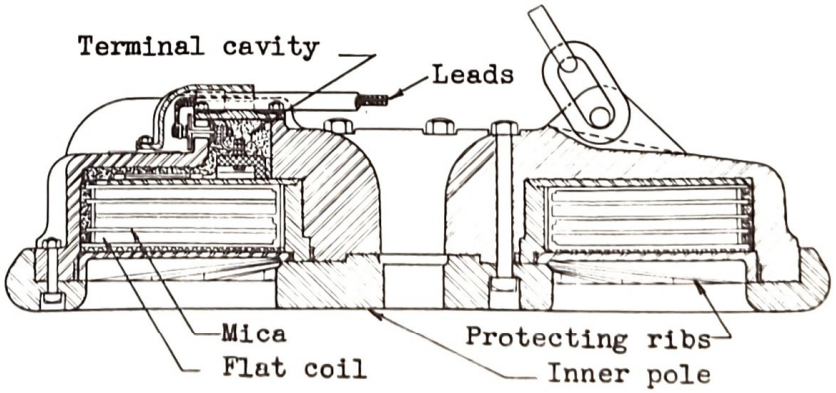


Fig. 28
Lifting magnet for handling iron and steel

These magnets save considerable time and labor because they require no slings or chains for holding a load.

Fig. 28 shows a typical magnet, consisting of a four-layer coil surrounded by a steel frame. The frame protects the winding and forms the magnetic circuit between the two poles, located at the center of the coil and at the outer ring. Between these two poles is a non-magnetic manganese steel casting with projecting ribs, which protects the coil and enables the magnet to withstand extremely severe service. The magnetic path between the faces of the two poles is completed through the material being handled.

A suitable controller must be provided to rapidly magnetize and demagnetize the lifting magnet. The construction and wiring diagram of a typical controller is shown in fig. 29. When it is desired to lift a load, the master switch S is moved to the "lift" position. This energizes coil C_1, which closes breakers 1 and connects the magnet across the line. The master switch will remain in this position until again moved by the operator.

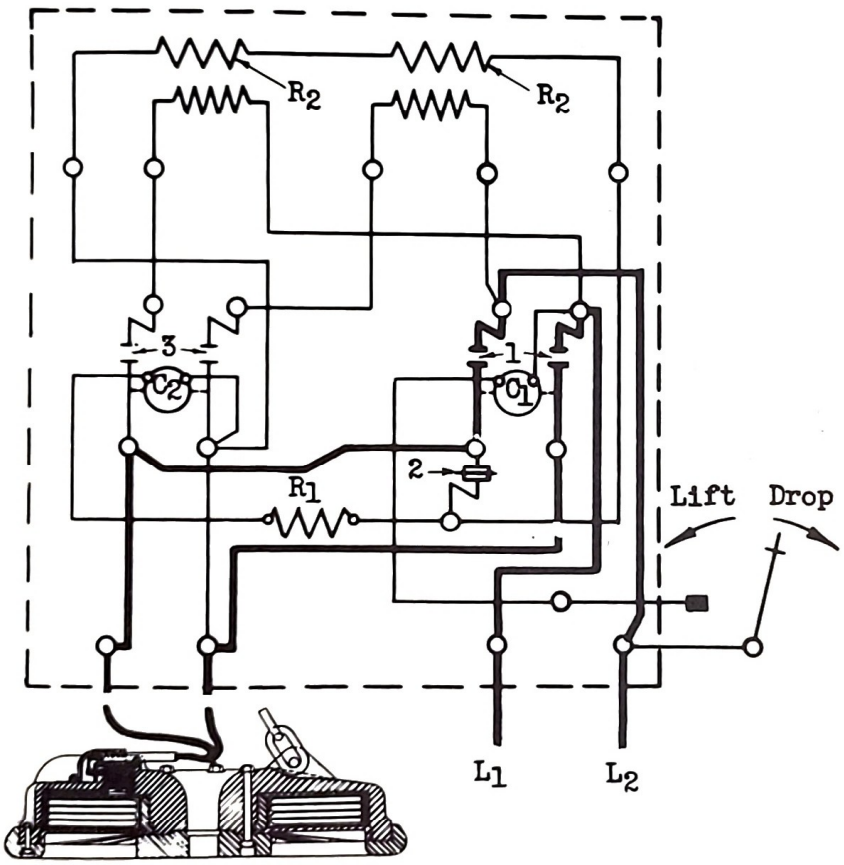


Fig. 29
Cutler-Hammer type controller for lifting magnets

When the operator wishes to drop the load, the master switch is moved to the "drop" position and left there. This allows breakers 1 to drop out and causes breaker 2 to close, thus connecting coil C_2 across the terminals of the magnet, with R_1 in series and R_2 in parallel with this coil. On dying out, the flux on the lifting magnet sets up a voltage which energizes coil C_2 for a few seconds (the time can be regulated within certain limits by varying R_1 and R_2). Breakers 3 are closed while C_2 is energized, thus placing a reverse voltage across the magnet terminals. As a result, a reversed current flows through the coil of the magnet, setting up a flux that neutralizes the residual magnetism. This allows the load to drop off within 1 to 3 seconds, whereas about 15 seconds would be required without a reverse voltage.

MAGNETIC CHUCKS.- Magnetic chucks are sometimes used on planers and grinders to avoid the use of clamps. One type, which consists of many coils surrounded by a steel housing, is shown in fig. 30. The upper portion of the housing is divided into a number of sections. These are magnetized by the coils to form poles of alternate polarity. Placing the work on these poles closes the magnetic circuit, thus holding it firmly in place.

MAGNETIC CLUTCHES.- Clutches are used to connect and disconnect a load from its driving source. They consist of two elements--a friction element and a field member for exerting force on the friction element. Fig. 31 shows the construction of one type.

One member carries a double friction lining, which lies between two rings attached to the field and the armature. When the field coil is energized, the field ring and the armature ring (see fig. 31) are drawn together, thus clamping the friction lining. This produces a driving force.

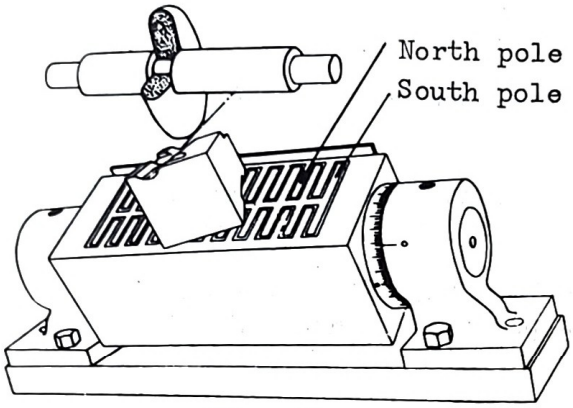


Fig. 30
Commercial magnetic chuck

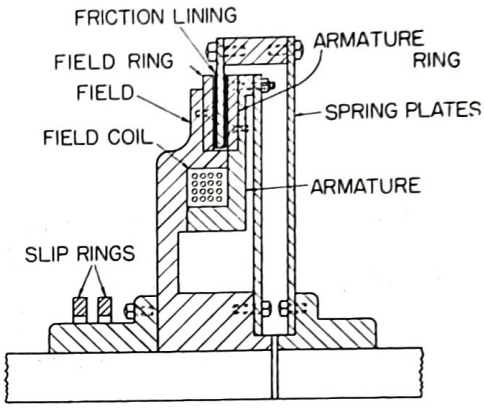


Fig. 31
Magnetic clutch

MAGNETIC BRAKES.- A type of brake frequently found on direct current cranes is shown in fig. 32. The field winding of this brake is connected in series with the armature circuit. When the power is removed from the motor, or when it is no longer supplied, due to some other reason, such as a blown-out fuse, the coil becomes de-energized and the heavy spring S applies the friction brake immediately. When power is supplied to the motor, the magnet becomes energized and pulls arm A downward. This action raises the shoes from the brake wheel, thus allowing the armature to rotate freely.

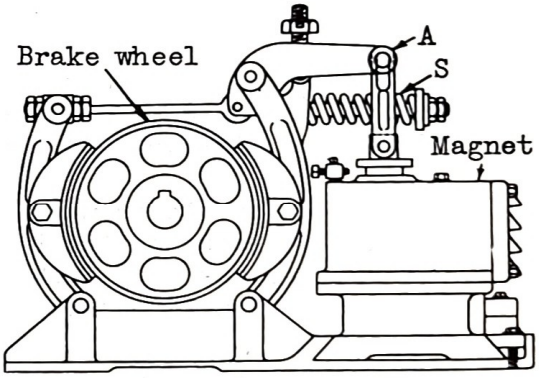
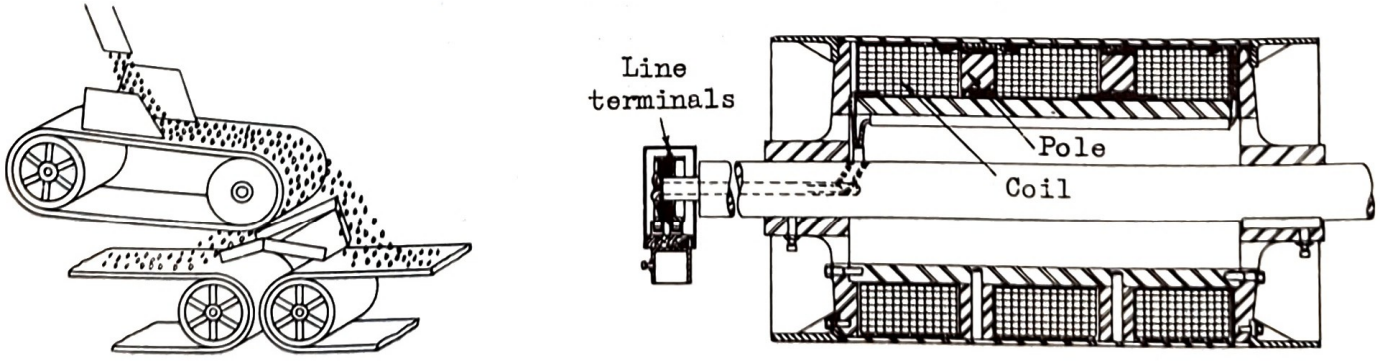


Fig. 32 A type of brake generally found on cranes

MAGNETIC SEPARATOR PULLEY.- Separator pulleys are used mostly in foundries for removing particles of iron and steel from pulverized materials. The material is delivered onto a moving belt (fig. 33a), which passes over the magnetic pulley. The magnetic material sticks to the belt and is therefore carried further around than the non-magnetic material with which it is mixed. Thus the two drop on different conveyors. The magnetic pulley consists simply of a series of alternate north and south poles, each extending entirely around the pulley (see fig. 33b).



(a) (b)

Fig. 33 Magnetic separator

MAGNETIC PULL.- It was shown in lesson 17 that magnetic lines passing between iron or steel poles tend to pull them together. This pull may be calculated by the equation

$$F = \frac{B^2A}{7213 \times 10^4} \qquad (13)$$

where F = force in pounds, B = flux density in each pole, and A = cross-sectional area of each pole.

EXAMPLE.- The magnetic circuit shown in fig. 34 has a cross section of 2 square inches. If the magnetizing action is produced by 280 ampere-turns, compute the attractive force between A and B.

The ampere-turns per inch is H = 280 ÷ 14 = 20. Fig. 22 shows that 20 ampere-turns per inch set up 68,000 magnetic lines per square inch. Substituting in equation 13,

$$F = \frac{68{,}000^2 \times 2}{7213 \times 10^4} = 128.2 \text{ lbs per pair of poles}$$

$$\text{Total force} = 128.2 \times 2 = 256.4 \text{ lbs}$$

In the design of a plunger electromagnet, a low flux density should be selected for the poles (about 50,000 lines per square inch), so that the m m f (ampere-turns) required for the air-gap, and therefore the amount of copper, will not be excessive.

EXAMPLE.- The electromagnet shown in fig. 35 is connected to a 50 volt source, has a .5 inch travel, and exerts a 20 pound pull. Determine the size of the wire, the number of turns, and the lettered dimensions.

The cross section of the plunger is

$$A = \frac{7213 \times 10^4 F}{B^2} = \frac{7213 \times 10^4 \times 20}{50{,}000^2}$$

A = .577 square inches

Making the plunger square, then M = $\sqrt{.577}$ = .76 inch.

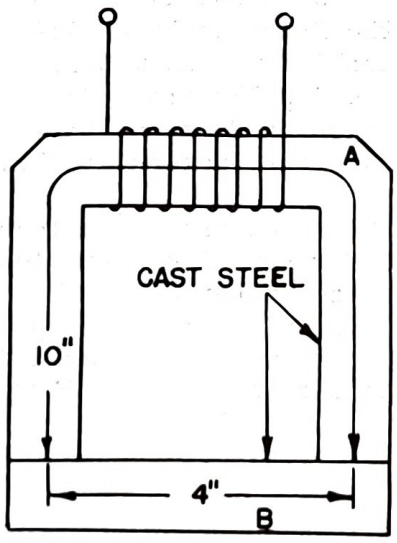


Fig. 34
Horseshoe electromagnet

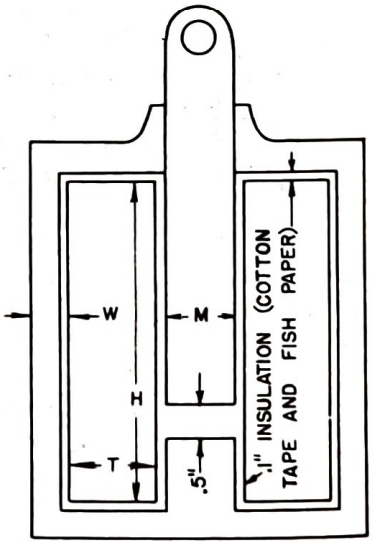


Fig. 35
Plunger electromagnet

Determining the cross section of the flux in the air-gap by substituting in equation 10 (lesson 19), A = (.76 + .5)(.76 + .5) = 1.59 square inches. The total flux in the plunger, and also in the air-gap, is 50,000 × .577 or 28,850 lines, and the flux density in the air-gap is B_a = 28,850 ÷ 1.59 or 18,145 lines.

The number of ampere-turns required to force the flux through the steel is very small compared to the number required to force the flux through the air-gap, and consequently, only the ampere-turns required for the air-gap will be considered. Substituting in equation 9 (lesson 19), IN_a = .313 × 18,145 × .5 = 2839.69 ampere-turns.

Selecting a coil thickness (T) of 1 inch and allowing .2 inch for insulation thickness, the average length per turn is $l_t = 4(.76 + 1 + .2) = 7.84$ inches. Substituting in equation 12, then,

$$\text{(m)} = \frac{10.7 \times 7.84 \times 2839.69}{12 \times 50} = 397$$

No. 24 gage wire, which has an area of 404 circular mils is the nearest size to this calculated value.

An air cooled coil will not overheat if the wire has a cross section of 1200 circular mils per ampere. Figuring the coil current on this basis, I = 404 ÷ 1200 = .337 ampere.

The number of turns in the coil is N = IN ÷ I = 3839.69 ÷ .337 = 11,394. Single cotton covered wire will be selected, since it has sufficient insulation for 50 volts. According to Table II in lesson 13, 1700 turns of No. 24 gage, single cotton covered wire occupies one square inch. Then the cross section of the coil will be 11,394 ÷ 1700 or 6.7 square inches. Since the coil is one inch thick, its height must be 6.7 inches.

The section of the core surrounding the coil should have a flux density that does not exceed the saturation point, otherwise a high m m f will be required for this part of the magnetic circuit, which has been neglected. The amount of flux in this portion of the magnetic circuit is 28,850 ÷ 2 = 14,425 lines. Considering that this circuit is made of cast steel, for which a suitable flux density is 60,000 lines per square inch, the cross section of the surrounding portion must be 14,425 ÷ 60,000 or .24 square inch. It is desirable to make this cross section the same depth as the plunger, which is .76 inch. Then W will be .24 ÷ .76 = .318 inch.

HOME WORK

1. In fig. 34, with what force is armature B attracted if 2 amperes flow through the coil and it has 200 turns (both A and B are cast steel)?

2. With what force is part B in fig. 34 attracted if its poles are each 1/4 inch from those of part A (the m m f required to force the flux through parts A and B is to be neglected)?

3. To ring the bell shown in fig. 36, the armature must be attracted with a force of 8 pounds. Parts A and E are made of cast steel and part E is circular in cross section. (Since the bell is used only for short intervals, consider the wire to have a cross section of 500 circular mils per ampere.) The coil is .5 inch thick and is connected to a 6 volt line. Determine (a) the diameter of E, (b) the size of the wire in the coil, and (c) the number of turns in the coil.

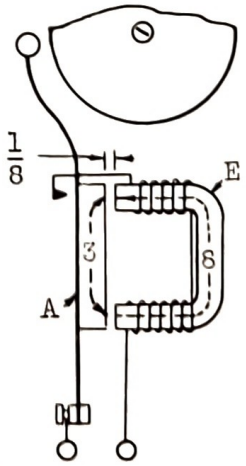
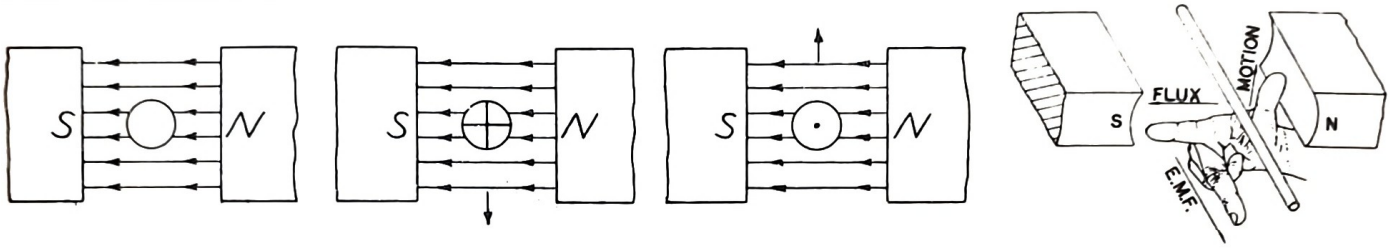


Fig. 36 Magnetic circuit of a bell

4. A cast steel electromagnet of the type shown in fig. 35 has a 3/4 inch travel, exerts a pull of 10 pounds, and is connected to a 40 volt line. Consider the coil to be one inch thick and determine (a) the size of the wire, (b) the number of turns in the coil, and (c) the dimensions shown in fig. 35.

A generator is a machine that converts mechanical energy into electrical energy. It consists fundamentally of a large number of conductors on an iron core, arranged to rotate in a magnetic field. The generator action depends upon the principle that an e m f is induced in a conductor cutting magnetic lines. Fig. 1a shows a conductor in a magnetic field. If it is moved either up or down, it cuts flux and an e m f is induced in it. If the conductor is moved either to the left or the right, however, it merely passes alongside the magnetic lines without cutting them, and therefore no e m f is induced.

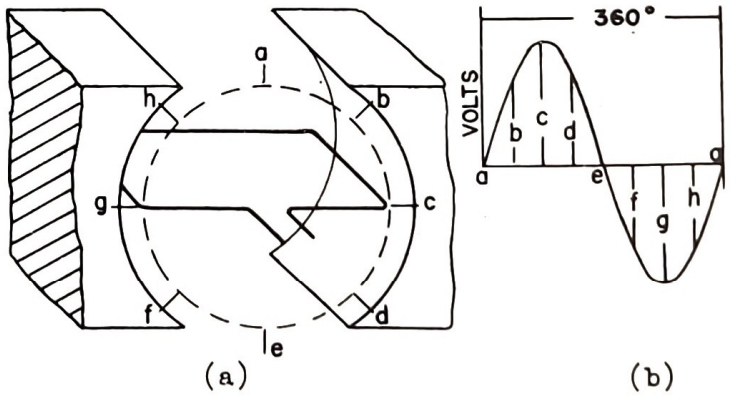


(a) (b) (c) (d)

Fig. 1 Method of producing an e m f

FLEMING'S RIGHT-HAND RULE.- There is a definite relation between the direction of flux, the direction of motion of the conductor, and the direction of the induced e m f. In fig. 1b the e m f is induced "in" when a conductor is moved downward. If the direction of motion is reversed, as indicated in fig. 1c, the direction of the e m f reverses. The direction of the e m f induced in a conductor can be found as follows: Extend the thumb, the forefinger, and the middle finger of the right hand at right angles to one another (fig. 1d). Point the forefinger in the direction of the flux and the thumb in the direction in which the conductor is moving. Then the middle finger will point in the direction of the induced e m f.

VOLTAGE IN A ROTATING COIL.- Suppose that a single turn coil (fig. 2a) rotates in a uniform magnetic field at a constant speed. As the coil changes position, the induced e m f changes, but the e m f induced in one side always adds to that induced in the other. When the coil is in position a, the e m f generated is zero, because the coil sides are not cutting magnetism, but are moving parallel to it. When the coil is in position b, its sides are moving at an angle to the flux, and therefore a low e m f is generated (indicated by b in fig. 2b). When the coil is in position c, the coil sides are moving at right angles to the flux, and are therefore cutting the flux at the maximum rate. Hence, at this instant the generated e m f is maximum. At position d, the generated e m f is less because the coil sides are again cutting at an angle, as at b. At e no lines are being cut, and as at a, no e m f is generated. At f, each coil side moves under a pole of opposite polarity, and the direction of the generated e m f is reversed. The e m f is maximum in this direction when the coil is at g and zero when it is again at a. This cycle repeats each revolution.



(a) (b)

Fig. 2 Nature of the e m f induced in a coil

The alternating e m f generated in a coil is impressed on an external circuit by means of two slip rings, one connected at each end of the coil (fig. 3). Stationary brushes resting on the rings connect the coil to the external circuit.

If the two slip rings are replaced by a single split ring (fig. 4a), called a commutator, the connection of the coil reverses at the same time that the induced e m f reverses. Therefore, the e m f impressed on the external circuit always remains in one direction. With a single coil, the voltage supplied will of course not remain steady, but will pulsate as indicated in fig. 4b. A pulsating voltage would be undesirable commercially, and furthermore, a single coil would utilize very little of the space available on the cylindrical iron core.

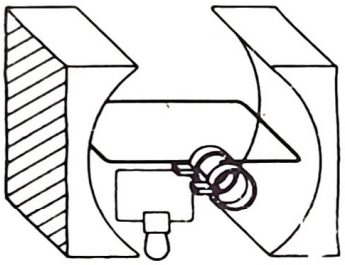


Fig. 3 External load connected to a rotating coil through slip rings

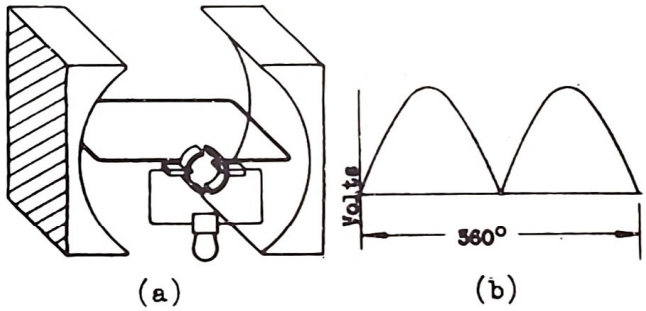


Fig. 4 External load connected to a rotating coil through a commutator

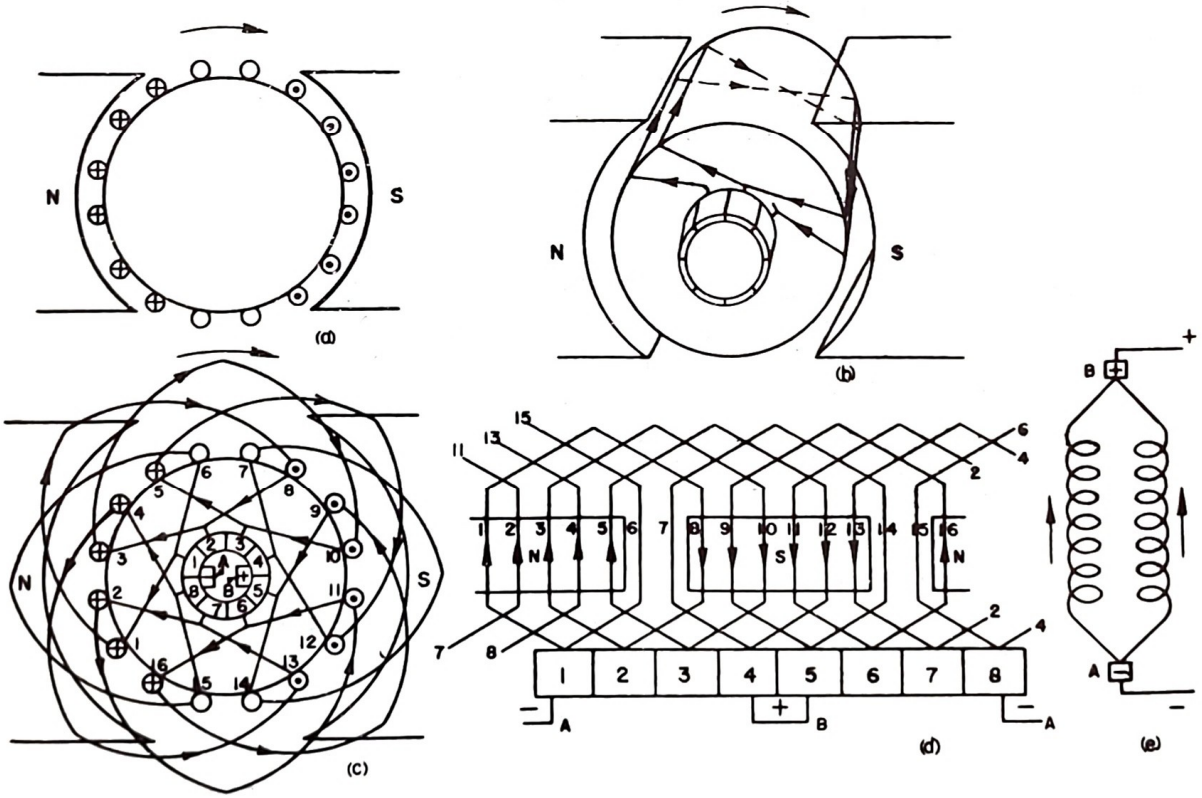


Fig. 5 Two pole winding

LAP WINDING.- The undesirable features of a single coil may be eliminated by placing a number of such coils on a cylindrical iron core (fig. 5a). If these are rotated in a clockwise direction, the voltages induced in the sides under the north poles are "in", and the voltages induced in the sides under the south poles are "out".

These coils may be connected in such a manner that their induced voltages are additive from one brush to the other. A common method of doing this is illustrated in fig. 5b, which is known as a lap winding because the successive coils overlap. A complete view of this winding is shown in fig. 5c and a developed view in fig. 5d. One path and the direction of the voltage induced in it may be traced by starting with brush A and proceeding as follows: A-1-8-3-10-5-12-B. Another path may be traced from A as follows: A-4-13-2-11-16-9-B. The coil with sides 6 and 15 is short-circuited by brush A, and the coil with sides 7 and 14 is short-circuited by brush B. This is permissible because these coils are not cutting magnetism and have no voltage induced in them. Thus the winding has two paths, and the direction of the voltage in each tends to send the current from brush A to brush B. This is shown in fig. 5e. With reference to the winding itself, these voltages are equal and opposite, and no current flows through the two paths when no external load is connected to the brushes. With reference to an external load, however, the voltages in the two paths act in the same direction, sending current through the external load. The current through each path will be half the load current.

The voltage induced in a path is the sum of the voltages induced in the coils of that path. When one coil moves past a brush or out of a path, another coil moves into the path. Fig. 6 shows how the voltage of one path is made up. Since the coils are displaced from each other by $360 \div 8 = 45°$, the voltage waves are displaced from each other by the same angle. These voltages are plotted separately. The generated voltage in a path at any instant is the sum of the individual voltages in that path at the same instant. This sum varies slightly, as indicated in fig. 6. The number of coils is much greater in most windings, and the voltage per path (or at the terminals of the machine) is nearly constant.

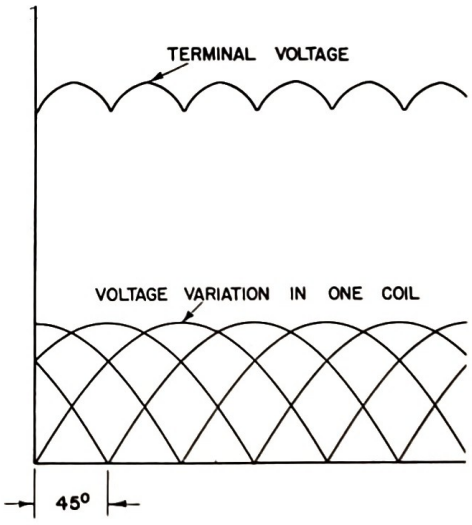


Fig. 6 Generated e m f in each path of a generator

Armatures with only one winding, as shown in fig. 5, are said to be simplex wound. Those with more than one winding are said to be multiplex wound, and are to be considered later.

PITCH.- If a coil spans from the center of one pole to the center of an adjacent pole, it has a full pitch. If the coil spans less than full pitch, it has a fractional pitch, which should not be less than .9 full pitch. If the pitch is too small, an appreciable reduction in generated e m f results. The fractional pitch type of winding is in general use, because it produces less sparking and because it requires less copper, which means lower armature resistance.

The most convenient way of expressing the span of a coil is in terms of the slots. To span from the center of one pole to nearly the center of an adjacent pole, a coil must span nearly 1/2 the distance around the armature in a 2 pole winding, 1/4 the distance in a 4 pole winding, 1/6 the distance in a 6 pole winding, etc. Then for any number of slots S and poles P, the slot span is

$$y_s = \frac{S}{P} \text{ (preferably slightly less)} \qquad (1)$$

DOUBLE LAYER WINDING.- When the coil sides are placed in one layer, as shown in fig. 5, it is difficult to arrange their ends so that they will pass each other. In order to avoid this difficulty, the coils are generally arranged in two layers, as shown in figs. 7 and 13a. Each coil has one of its sides at the top of a slot and the other at the bottom of some other slot. The coil ends will then lie side by side.

Each coil is usually wound with the proper number of turns by a machine, and is then wrapped with varnished cambric or mica tape, either of which is covered with cotton tape. As far as connecting the coils is concerned, the number of turns per coil is immaterial. For simplicity, then, the coils in winding diagrams will be represented as having only one turn.

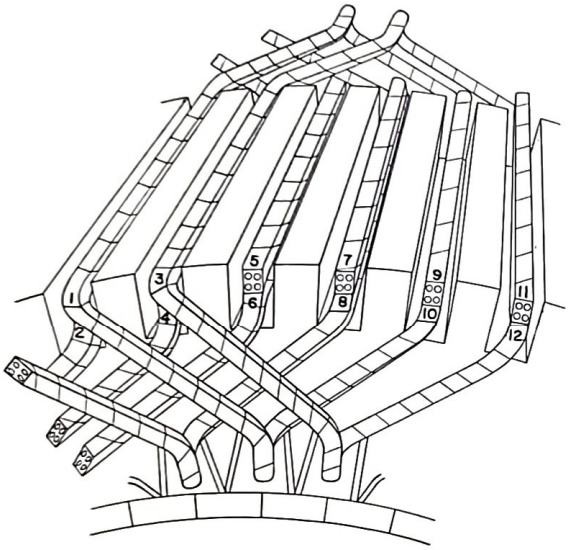


Fig. 7 Section of a two layer winding

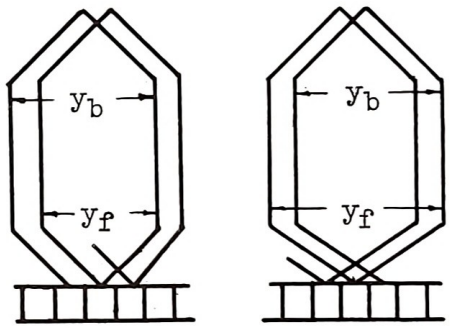


Fig. 8
Progressive and retrogressive lap windings

WINDING PITCH.- In a two layer winding it is desirable to number the coil sides rather than the slots, in which case the rules established will apply to all windings of a given type. The coil sides are numbered as indicated in figs. 7 and 13a, those at the top of the slots being given odd numbers and those at the bottom being given even numbers. The number of coil sides spanned at the pulley end is called the back pitch, denoted by y_b (fig. 8). This back pitch equals the coil sides per slot (C_s) times the slot span (y_s) plus 1. Expressing this by means of an equation,

$$y_b = C_s y_s + 1 \qquad (2)$$

The commutator pitch, denoted by y_c, is simply the number of segments spanned between the start end and the finish end of a coil. In a simplex lap winding, $y_c = 1$.

The number of coil sides spanned at the commutator end is called the front pitch, denoted by y_f. This span may be greater or less than y_b, but is never equal to it. If y_f is less, the winding is progressive, advancing in the clockwise direction (fig. 8a), and if y_f is greater, the winding is retrogressive, advancing in the counterclockwise direction (fig. 8b). In either case, y_b and y_f differ by 2. Therefore,

$$y_f = y_b \pm 2 \qquad (3)$$

When the negative sign is used, the winding is progressive, and when the positive sign is used, the winding is retrogressive. A retrogressive winding is seldom used because it requires more copper.

EXAMPLE.- A 4 pole, simplex lap wound armature contains 21 slots and has two coil sides per slot. What is (a) the slot span? (b) The back pitch? (c) The commutator pitch? (d) The front pitch?

(a) $y_s = \frac{S}{P} = \frac{21}{4} = 5\frac{1}{4}$

Since a coil can span only a whole number of slots, in solving this problem the fraction 1/4 is dropped, making $y_s = 5$.

(b) $y_b = C_s y_s + 1 = 2 \times 5 + 1 = 11$

The back pitch of the first coil will therefore be from 1 to 12.

(c) As previously explained, for a simplex lap winding, $y_c = 1$.

(d) Considering a progressive winding, then,

$y_f = y_b - 2 = 11 - 2$ or 9

This winding is shown in figs. 9 and 10 (in fig. 10 the winding is rolled out into a plane).

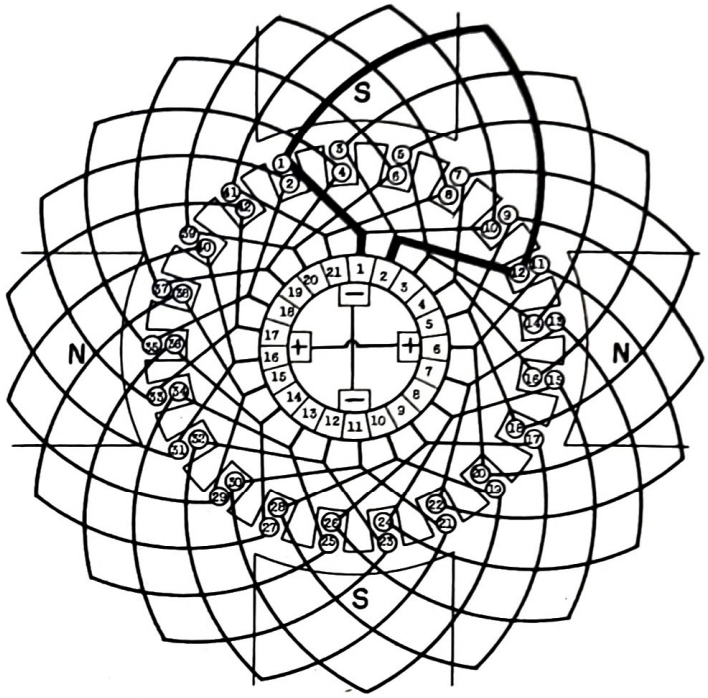


Fig. 9 A 21 slot, 4 pole simplex lap winding

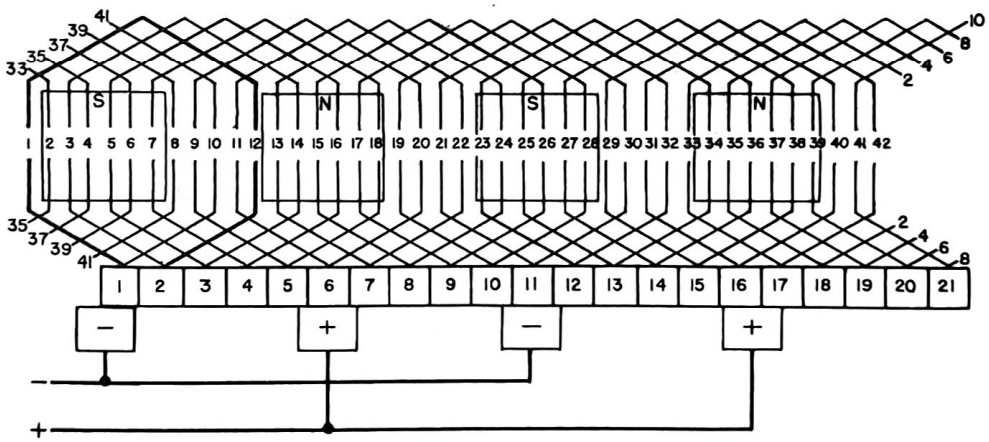


Fig. 10 Developed view of fig. 9

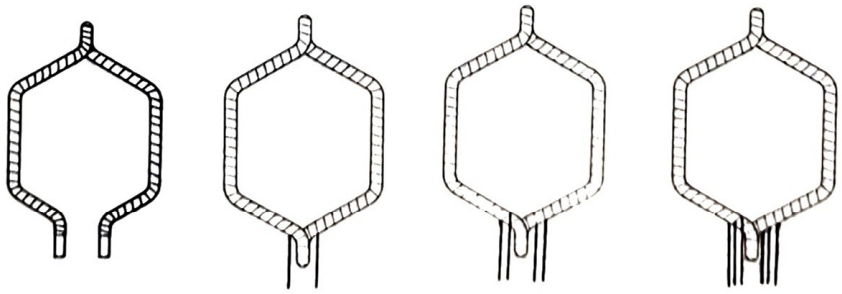
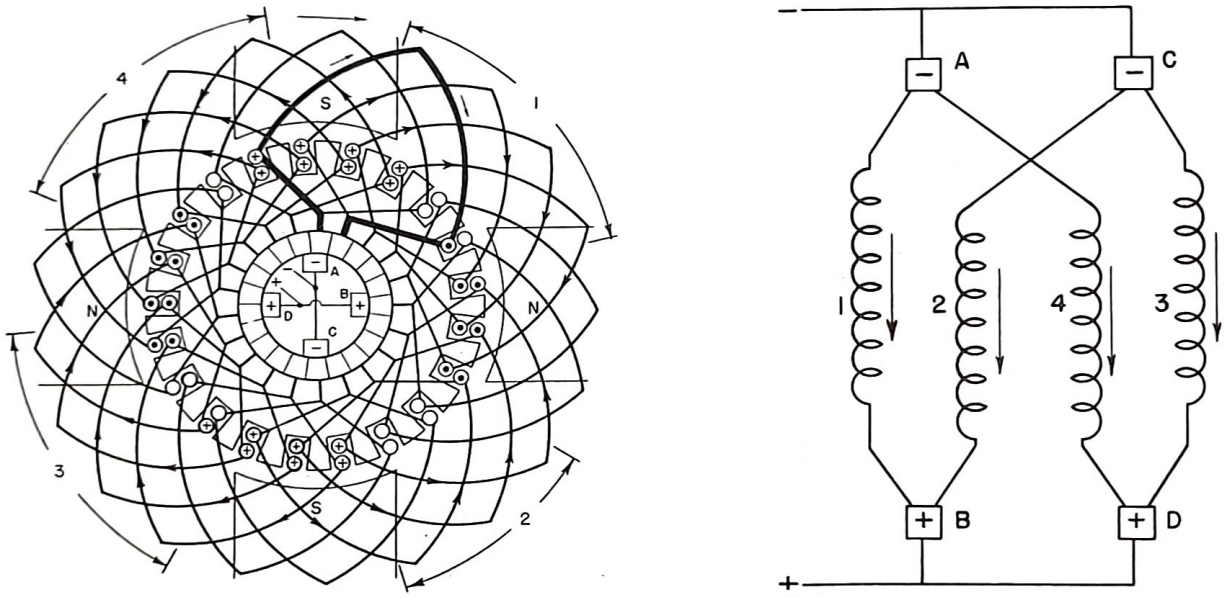


Fig. 11 Single and multiple coils

PATHS IN A SIMPLEX LAP WINDING.- In the four pole, simplex winding shown in fig. 12a (which is the same as fig. 9), there are four parallel paths between the negative and positive leads. One path is traced from the negative lead to brush A, through coils 1, to brush B, and then to the positive lead. A second path is traced from brush A, through coils 4, to brush D, to the positive lead. A third path is traced from the negative lead to brush C, through coils 2, to brush B, to the positive lead. A fourth path is traced from brush C, through coils 3, to brush D, and then to the positive lead. The connections of these paths are shown in a simplified manner in fig. 12b.

The winding shown in fig. 12a has 4 poles and 4 paths. A 6 pole winding has 6 paths, an 8 pole winding has 8 paths, etc. In any simplex lap winding, then, there are always as many paths as there are poles.

If each path of the winding shown in fig. 12b delivers 10 amperes at 120 volts, each brush will carry 20 amperes and the machine will deliver 40 amperes at 120 volts.



(a) (b)

Fig. 12 Parallel paths in an armature

HOME WORK

1. A 4 pole, lap wound armature has 21 slots and 21 segments. If the winding is progressive, what is (a) the back pitch? (b) the commutator pitch? (c) the front pitch?

2. Answer parts a, b, and c in problem 1 if the winding is retrogressive.

3. Make a diagram of the winding in problem 1.

4. How many paths has (a) an 8 pole, simplex lap winding? (b) a 10 pole simplex lap winding?

5. An 8 pole, 240 volt, simplex lap wound armature delivers 125 amperes. Determine (a) the voltage per path, (b) the current per path, and (c) the current per brush.

6. Using a cross section of 600 circular mils per ampere, what size wire is required for the armature of problem 5?

MULTIPLE COILS.- Although two coil sides per slot are used in many machines, in others a large number of slots would be required to keep the voltage between adjacent commutator segments at a low value. In some machines this would require small slots, in which case the ratio of the copper cross section to the slot cross section would be low. Also, the teeth roots would be so narrow that the teeth would be mechanically weak. This undesirable construction is eliminated by using less slots than commutator segments and placing more than two coil sides in each slot.

When more than two coil sides are to be placed in each slot, the armature is wound with multiple coils. A multiple coil consists of two or more coils taped together (fig. 11b) and inserted in a slot as a unit, one side filling the upper half of one slot and the other side filling the lower half of another slot. These coil sides are numbered as shown in fig. 13b and are connected in the same manner as single coils.

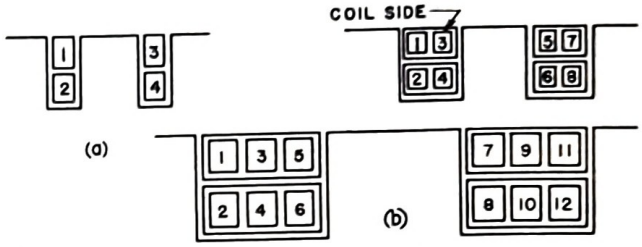


Fig. 13 Number of coil sides per slot

Irrespective of the type of winding, there are always two coil sides connected to each segment, or an armature always has twice as many coil sides as segments. Then an armature with twice as many slots as segments (fig. 5) must have one coil side per slot, one with the same number of slots as segments (fig. 9) must have two coil sides per slot, one with half as many slots as segments must contain four coil sides per slot, etc. The number of coil sides per slot may be determined by the following equation (s = the number of segments):

$$C_s = \frac{2s}{S} \qquad (4)$$

EXAMPLE.- A 4 pole simplex lap winding has 17 slots and 34 segments. What is (a) the back pitch? (b) the commutator pitch? (c) the front pitch?

(a) $y_s = \frac{S}{P} = \frac{17}{4} = 4\frac{1}{4}$

$$C_s = \frac{2s}{S} = \frac{2 \times 34}{17} = 4$$

Making $y_s = 4$, then

$y_b = C_s y_s + 1 = 4 \times 4 + 1 = 17$

(b) $y_c = 1$

(c) Considering a progressive winding, $y_f = 17 - 2 = 15$.

This winding is shown in fig. 14.

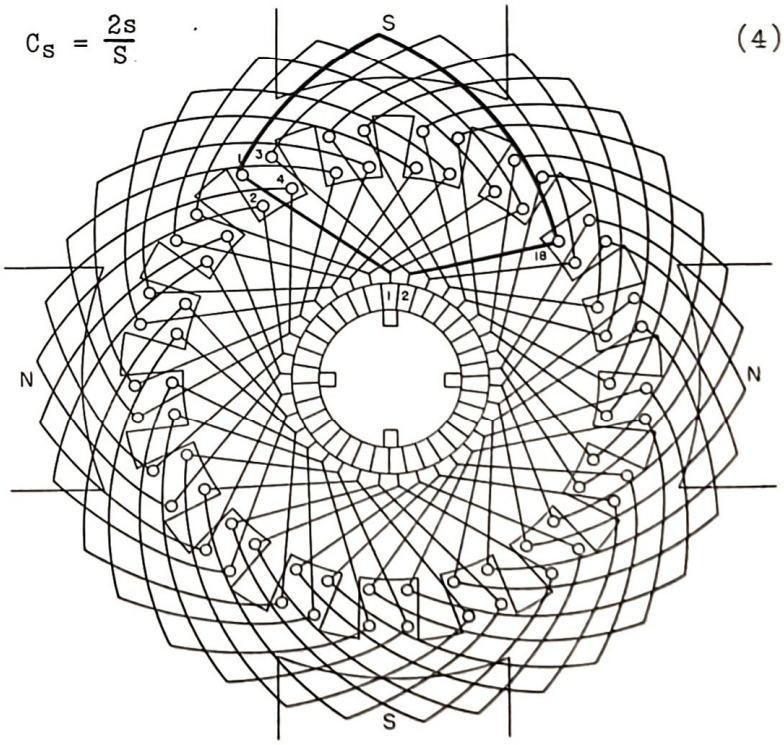


Fig. 14 Simplex lap winding with twice as many segments as slots

POSITION OF BRUSHES.- In the windings considered, the terminals of each coil connect to two segments midway between the coil sides. This method of connecting the coils is the most common because it requires the shortest coil leads.

With such a winding, the brushes are placed in line with the pole centers, so that the coil voltages add in each path, and so that the brushes short-circuit coils only while they are in the neutral plane. If a coil is short-circuited while it is not in the neutral plane, a large current will circulate through it and the short-circuiting brush. Then a severe spark will occur at the instant that the brush breaks away from one of the two segments connected to the short-circuited coil.

In some machines the bearing-bracket arms are in line with the poles. In this case it is desirable to have each brush in line with a point midway between the pole tips, so that they are not hidden under the arms, where they are inaccessible. For this position of the brushes, the coils are connected to the segments as shown in fig. 15.

Before an armature is stripped for the purpose of rewinding it, the coil connections should be observed, because such connections depend upon the position of the brushes relative to the poles. If the coil leads are connected incorrectly, relative to the position of the brushes, sparking will occur unless the brushes are shifted. This usually cannot be done.

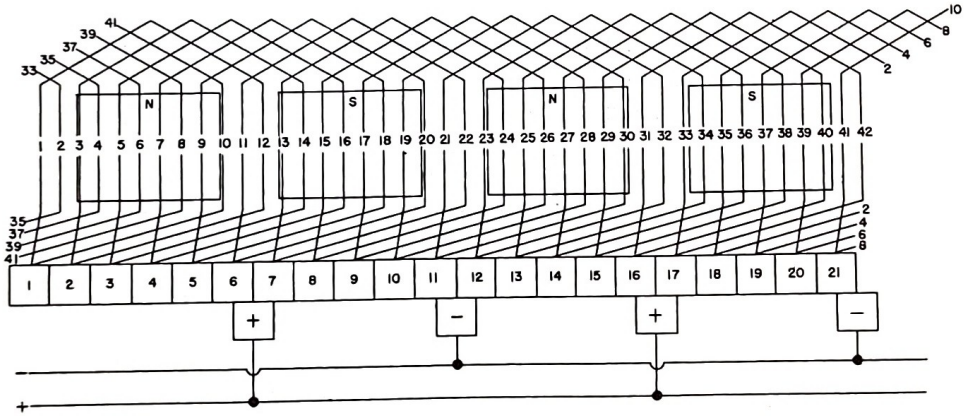


Fig. 15 Winding with brushes in line with a point midway between pole tips

DUPLEX LAP WINDING.- An armature that supplies a high current usually has several windings, each with an equal number of segments. Fig. 16 shows a 4 pole winding which occupies alternate slots and connects to alternate segments. In this case y_b is 13, since the first coil spans from 1 to 14. Coil side 14 connects back to coil side 5, making $y_f = 9$. Then the front pitch differs from the back pitch by 4 instead of by 2, which was the case in the simplex winding. Moreover, the commutator pitch is 2 instead of 1.

Since this winding occupies only alternate slots and connects to alternate commutator segments, a similar winding may be placed in the vacant slots and connected to the remaining segments. This second winding will obviously have the same back, front, and commutator pitches as the first.

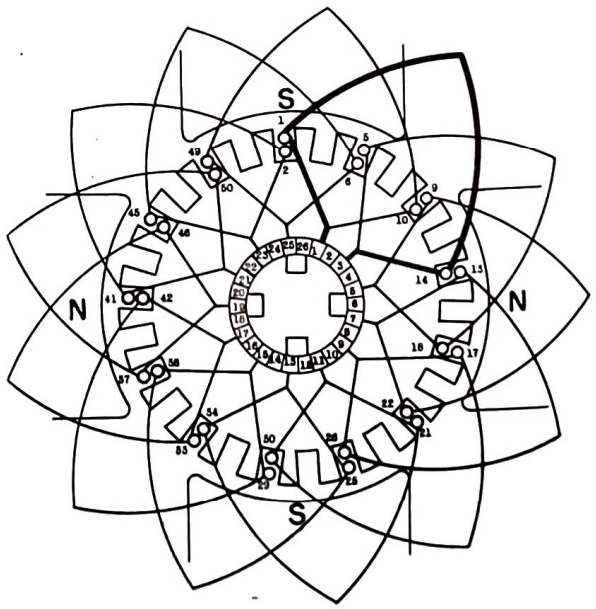


Fig. 16 A duplex, double reentrant lap winding (only one winding shown)

Although these two windings are insulated from each other, they are connected together by the brushes, each of which must cover at least two segments. Then each brush will connect to both windings at all times, permitting all the paths to supply current continuously. The two windings are therefore in parallel, and since each winding has four paths, the armature will have twice as many paths as there are poles. The armature is said to be wound duplex because it has two windings, and is said to be double reentrant because each winding reenters upon itself.

Of course three windings could be placed on an armature core, making the armature triplex lap wound, etc. Regardless of the multiplicity of a winding, the number of paths is

$$b = mP \qquad (5)$$

where m = the number of windings and P = the number of poles.

If the number of slots and segments in fig. 16 were one more or less than 26, the first winding would not close, and the complete winding would close only after the second winding was placed on the armature. This is illustrated by the 25 slot armature in fig. 17. It should be observed that the first winding does not return to segment 1, as does the winding in fig. 16, but terminates at 2. The second winding, shown with dotted lines, starts at segment 2 and terminates at segment 1. This duplex winding is single reentrant because it returns to the starting point only after the armature is completely wound. As in fig. 16, the brushes must be wide enough to cover at least two segments. The difference between the windings of figs. 16 and 17 is illustrated in a simple manner in fig. 18. The two windings have the same number of paths and practically the same number of coils per path, and therefore are the same electrically.

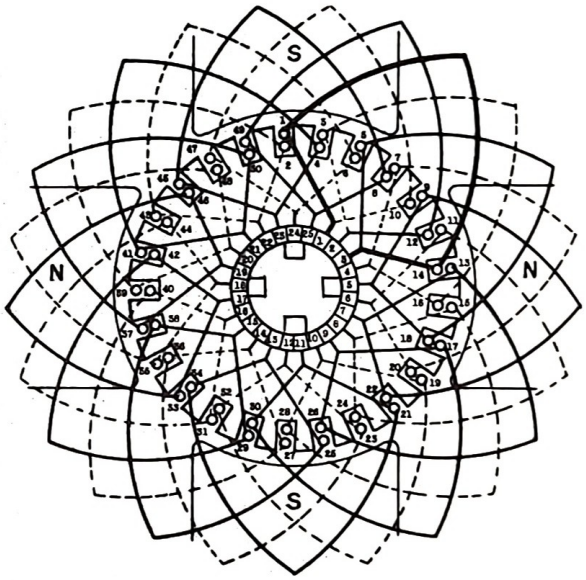
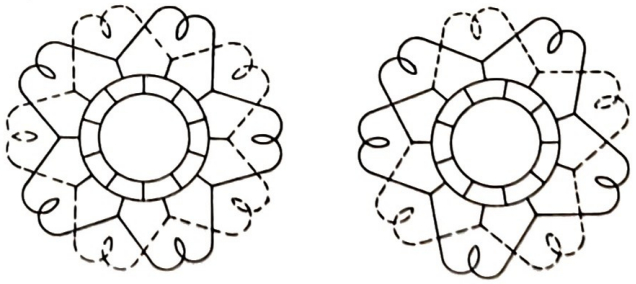


Fig. 17 Duplex, single reentrant lap winding (one winding is shown dotted)

In the foregoing it was shown that an armature with two windings is duplex, one with three windings is triplex, etc. If all the winding on an armature must be traced to return to the starting point, it is single reentrant; if only half the winding is traced before returning to the starting point, it is double reentrant; if only a third is traced before returning to the starting point, it is triple reentrant; etc.

The degree of reentrancy in a lap winding is found by dividing the number of segments by the multiplicity. If this gives a whole number, the winding is multiple reentrant, and if not, the winding is single reentrant.



(a) Double reentrant (b) Single reentrant

Fig. 18 Duplex lap winding shown in a simplified form

1. Determine the number of coil sides per slot in an armature that has (a) 21 slots and 42 segments; (b) 12 slots and 48 segments; (c) 20 slots and 10 segments.

2. Are one, two, or three wire coils required for an armature that has (a) 14 slots and 42 segments? (b) 20 slots and 20 segments? (c) 20 slots and 60 segments?

3. How many commutator segments may an 18 slot armature have?

4. Make a wiring diagram of a 4 pole, simplex lap winding with 18 slots and 36 segments. Place the brushes in line with the pole centers, number the coil sides, and show the slots.

5. Show a few turns of the winding of problem 4, considering each brush in line with a point midway between adjacent poles.

6. How many paths has an (a) 8 pole duplex winding? (b) A 10 pole triplex winding?

7. A 2 pole armature has 14 slots and 14 segments. Show a few coils of this winding if the armature is (a) simplex; (b) duplex; (c) triplex. Consider the brushes in line with the pole centers.

8. A 6 pole, duplex lap winding has 32 slots and 64 segments. Determine (a) the back pitch; (b) the commutator pitch; (c) the front pitch.

9. Show how a few coils of the winding in problem 8 are connected, considering the brushes in line with the pole centers.

10. Can the armature in problem 8 be wound (a) simplex? (b) Triplex?

11. Is the armature in problem 8 single or double reentrant?

12. An 8 pole, triplex wound armature supplies a current of 250 amperes. Determine (a) the current per path, and (b) the current per brush.

In a multiplex winding y_b is determined in the same manner as in a simplex winding (see equation 2), since in all cases this span should be slightly less than the distance from the center of one pole to the center of the next.

The front span y_f must differ from y_b by 2 in a simplex winding, by 4 in a duplex winding, by 6 in a triplex winding, etc. Then for any multiplicity (m) the front pitch (y_f) must differ from the back pitch (y_b) by 2m. That is,

$$y_f = y_b \pm 2m \tag{6}$$

For a simplex winding the commutator pitch (y_c) is 1, for a duplex winding it is 2, for a triplex winding it is 3, etc. Then for any multiplicity,

$$y_c = m \tag{7}$$

EXAMPLE.- A 4 pole, triplex lap winding has 24 slots and 24 segments. What is (a) the back pitch? (b) the commutator pitch? (c) the front pitch?

(a) $y_s = \frac{S}{P} = \frac{24}{4} = 6$

$$y_b = C_s y_s + 1 = 2 \times 6 + 1 = 13$$

(b) $y_c = m = 3$

(c) $y_f = y_b - 2m = 13 - 2 \times 3 = 7$

This 4 pole, triplex winding is shown in fig. 19.

If an armature is changed from simplex lap to duplex lap without making any other change, the number of paths is doubled and each path has half as many coils. The armature will then supply twice as much current at half the voltage. This principle is used when it is desired to reduce a voltage to half its value, as from 240 to 120 volts. A change from a simplex winding to a duplex winding is made merely by unsoldering the start end of each coil and connecting it one segment back of its previous location.

In the windings considered it will be noted that in every case the finish ends of adjacent coils, and also the start ends of adjacent coils, connect to adjacent commutator segments. This fact is utilized in connecting the coils to the commutator.

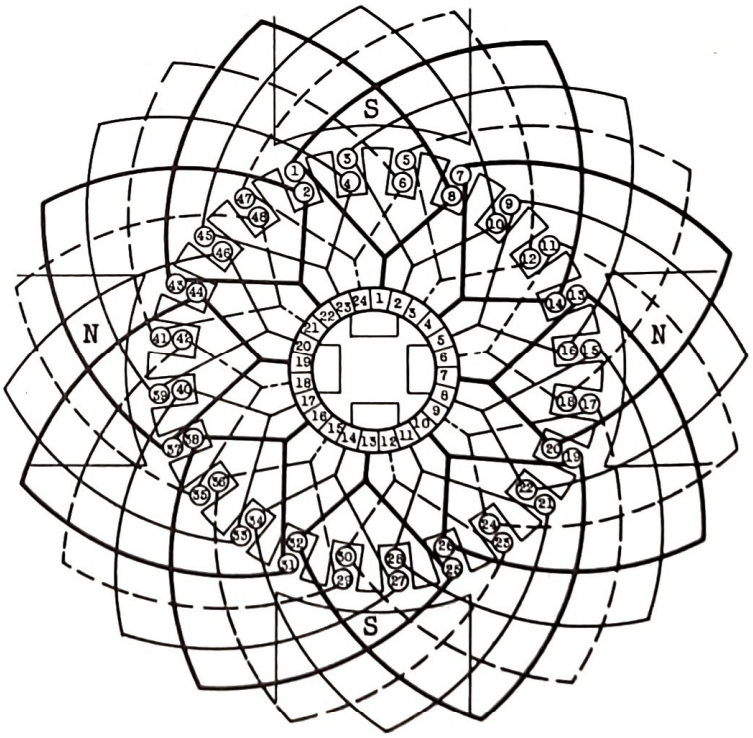


Fig. 19 Four pole, triplex, triple reentrant lap winding

When placing a lap winding on an armature, a good procedure is as follows:

(1) Insert all the coils in the slots.
(2) Mark the two segments to which the ends of the first coil should be connected.
(3) Beginning with the "finish" end of coil 1, connect the "finish" ends of adjacent coils to adjacent segments.
(4) Beginning with the "start" end of coil 1, connect the "start" ends of adjacent coils to adjacent segments.

REQUIREMENTS FOR LAP WINDING.- The most important requirements for lap winding may be summarized as follows:

(1) A lap winding can be placed on an armature with any number of slots (of course the number of commutator segments in a two layer winding must be equal to or a multiple of the number of slots).
(2) The brushes must be wide enough to cover at least m segments (where m is the multiplicity of the winding).
(3) There must be as many brushes as there are poles, and the brushes must be set so that they short-circuit only the coils cutting no flux.

ARMATURE WITH TWO COMMUTATORS.- Some armatures have two independent windings in the same slots, and each of these windings has its own commutator, one commutator being placed at each end of the core. This system has the advantage that the two windings can be connected in series or in parallel, and that it can be adapted to the three wire system (see lesson 15).

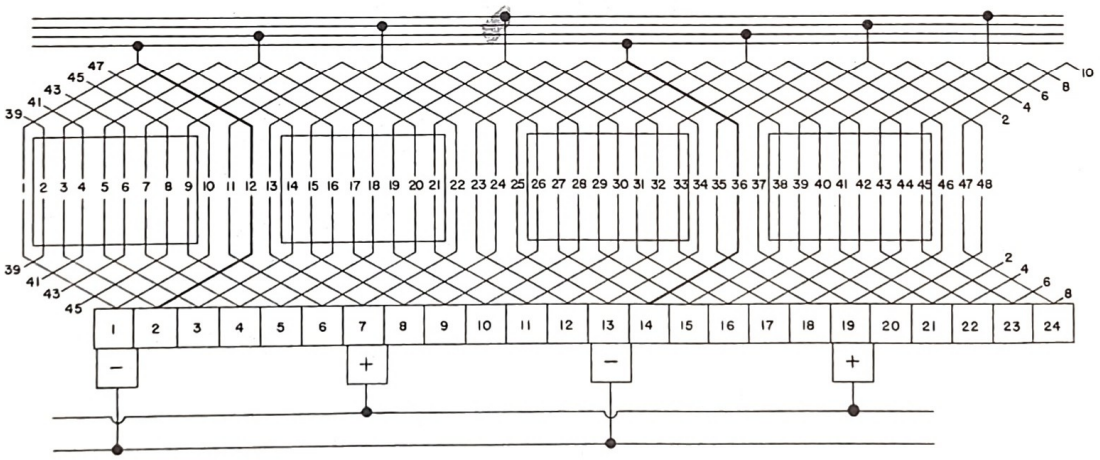


Fig. 20 Armature winding with equalizer connections

EQUALIZER CONNECTIONS.- Because of wear in the bearings, and for other reasons, the air-gaps in a generator become unequal, and therefore the flux in some poles becomes greater than in others. This causes the voltages of the different paths to be unequal. In a lap winding the paths connect to the negative line through the negative brushes, and connect to the positive line through the positive brushes. With unequal voltages in these paths, circulating currents will flow even if no current is supplied to an external load. If these currents are large, some of the brushes will be required to carry a greater current at full load than they were designed to carry, and this will cause sparking. To relieve the brushes of these circulating currents, points on the armature that are at the same potential are connected together by means of copper bars called equalizers. This is accomplished by connecting to the same equalizer the coils that occupy the same positions relative to the poles (fig. 20).

The equalizers provide a low resistance path for the circulating current, keeping it from passing through the brushes, and thus reducing sparking.

Equalizers should be used only on windings in which the number of coils is a multiple of the number of poles. For best results each coil should be connected to an equalizer, but this is seldom done. Satisfactory results are obtained by connecting about every third coil to an equalizer. To distribute equally the connections to the equalizers, the number of coils per pole must be divisible by the connection pitch.

EXAMPLE.- A 6 pole armature contains 54 coils. Suggest how equalizer connections should be made.

$$\text{Coils per pole} = \frac{54}{6} = 9$$

As the number 9 is divisible by 3, equalizer connections to every third coil will give good results.

HOME WORK

1. How many brushes are required in a lap winding?

2. A 4 pole, 120 volt generator with a simplex winding is rated at 10 kw. What is (a) the voltage and (b) the current per path at full load?

3. What would be the terminal voltage and line current at full load if the armature of problem 2 is reconnected duplex.

4. What is the minimum number of segments that each brush must cover in a (a) duplex winding? (b) Simplex winding? (c) Triplex winding?

5. What changes must be made in the commutator connection of a generator with a simplex wound armature to change its terminal voltage from 240 volts to 60 volts?

6. A 4 pole motor has 24 slots and 24 segments. Determine the possible equalizer connection pitches.

7. The finish ends (or the start ends) of adjacent coils connect what number of segments apart in a (a) simplex winding? (b) Duplex winding? (c) Triplex winding?

WAVE WINDING.- The essential difference between a lap winding and a wave winding is in the commutator connections. In a lap winding, the start end of the second coil connects to the finish end of the first, the start end of the third to the finish end of the second, etc. (fig. 21). With such connections, the coil voltages add. These voltages will also add if the coils occupying approximately the corresponding position under all the poles are connected in series (see figs. 22 and 25). The winding must not close after it passes once around the armature, but, if it is a simplex winding, it must connect to a segment adjacent to the first, and the next coil must lie adjacent to the first, as indicated in fig. 22. This is repeated each time around until connections are made to all the segments and all the slots are occupied, after which the winding automatically returns to the starting point. If, after passing once around the armature, the winding connects to a segment to the left of the starting point (fig. 22a), the winding is retrogressive. If it connects to a segment to the right of the starting point (fig. 22b), it is progressive. This type of winding is known as a wave winding because it passes around the armature in a wavelike form.

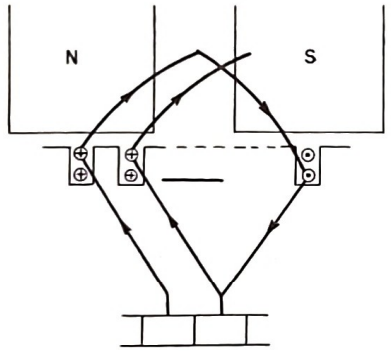
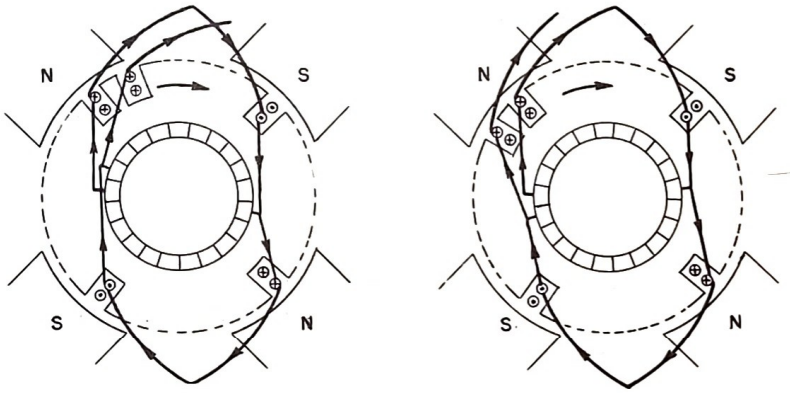


Fig. 21
Section of a lap winding



(a) (b)

Fig. 22 Retrogressive and progressive wave windings

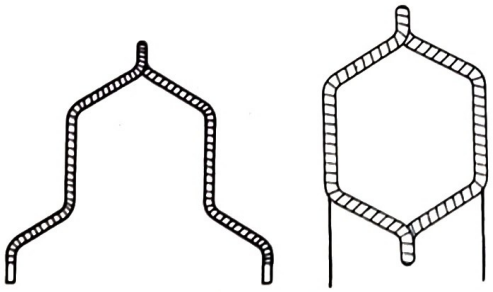


Fig. 23
Single and multiple turn coil

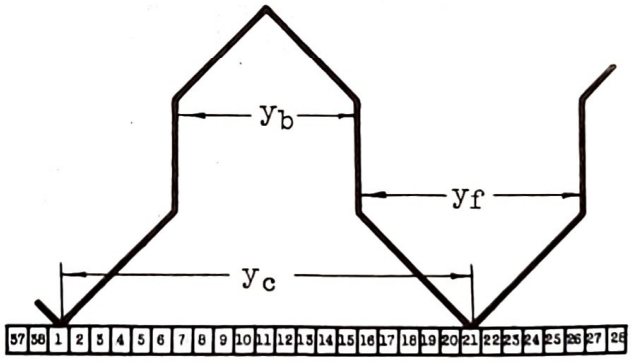


Fig. 24 Back, commutator, and front pitch in a wave winding

A coil for a wave winding may have more than one turn (fig. 23), but the number of turns does not affect the coil connections, and for simplicity in the illustrations, only one turn per coil will be shown.

In wave winding, as in lap winding, the number of coil sides spanned at the pulley end is known as the back pitch (y_b), the number of segments spanned at the terminals of the coils is known as the commutator pitch (y_c), and the number of coil sides spanned at the commutator end is known as the front pitch (y_f). This is indicated in fig. 24. In a wave winding, y_s and y_b are determined in the same way as in a lap winding.

In a simplex wave winding, the commutator pitch (y_c) times the number of coils that must be traced to pass once around the armature (which is always P/2 coils) equals the total number of commutator segments (C) plus or minus 1 (see fig. 21). That is,

$$y_c \frac{P}{2} = C \pm 1 \tag{8}$$

$$\text{or} \qquad y_c = \frac{2C \pm 2}{P} \tag{9}$$

where the minus sign indicates a retrogressive winding and the plus sign indicates a progressive winding.

In any winding the progress on the core must be exactly the same as on the commutator. This is illustrated in fig. 25, where the commutator pitch is 11 and the sum of the back and front span is 11 slots, which, when expressed in coil sides, equals the sum of the back and front pitch divided by 2. In a wave winding, then,

$$y_c = \frac{y_b + y_f}{2}$$

$$\text{or} \qquad y_f = 2y_c - y_b \tag{10}$$

In a wave winding, y_b, y_c, and y_f may be equal.

EXAMPLE.- An armature has 29 slots and 29 commutator segments. If it is to be wound simplex wave for 4 poles, determine (a) the back pitch, (b) the commutator pitch, and (c) the front pitch.

(a) $y_s = \frac{S}{P} = \frac{29}{4} = 7\frac{1}{4}$

Dropping the fraction,

$y_b = C_s y_s + 1 = 2 \times 7 + 1 = 15$

(b) Considering a retrogressive winding,

$$y_c = \frac{2C - 2}{P} = \frac{2 \times 29 - 2}{4} = 14$$

(c) $y_f = 2y_c - y_b = 2 \times 14 - 15 = 13$

Fig. 26 shows this winding.

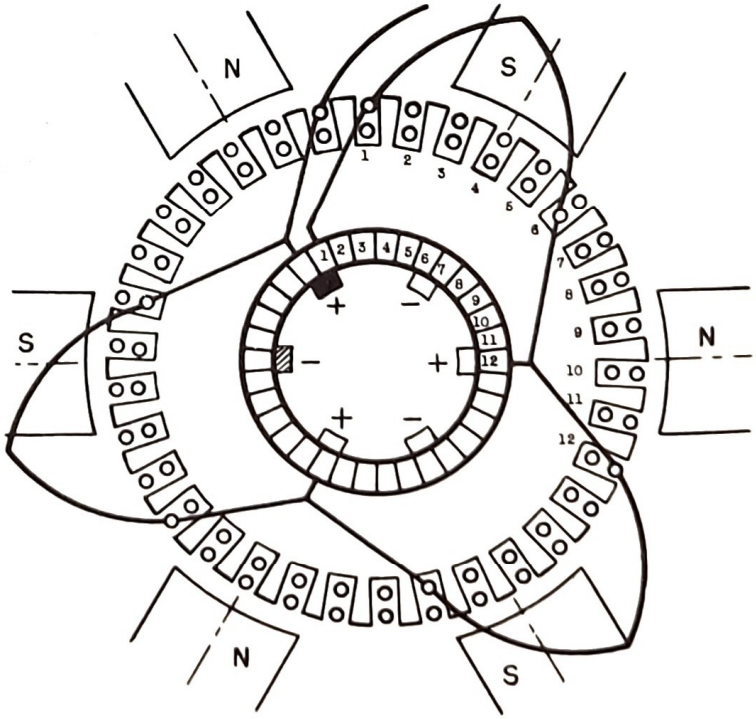


Fig. 25 A 34 slot, 6 pole wave winding

PATHS IN A WAVE WINDING.- In fig. 26 one path (indicated by heavy lines) may be traced by starting with the negative brush A and proceeding through the coil sides as follows: A-1-16-29-44-57-14-27-42-55-12-25-40-53-10-23-38-51-8-21-36-49-6-19-34-47-4-B. Another path (indicated by light lines) may be traced by starting from the negative brush C and proceeding as follows: C-18-3-48-33-20-5-50-35-22-7-52-37-24-9-54-39-26-11-56-41-28-13-58-43-30-15-2-45-D. The negative brushes short-circuit the coil having sides 31-46, and the positive brushes short-circuit the coil having sides 17-32. This is permissible, since these coils are not cutting flux. This winding, which is also shown diagrammatically in fig. 27a, has 4 poles and only two paths. A simplex winding with any other number of poles likewise has two paths. In any simplex winding, then,

$$b = 2 \qquad (11)$$

The winding shown in figs. 26 and 27a has the same number of brushes as there are poles. In this winding, the current passes through the two paths, through the two positive brushes to the positive line, and back through the negative brushes. In a wave winding, however, the brushes of like polarity are short-circuited together by coils in the neutral plane. In figs. 26 and 27a, then, if brushes C and D are removed, the current will pass through the two paths, through the positive brush B to the positive line, and back through the negative brush A (fig. 27b). Therefore, in any wave winding, only one positive and one negative brush are required.

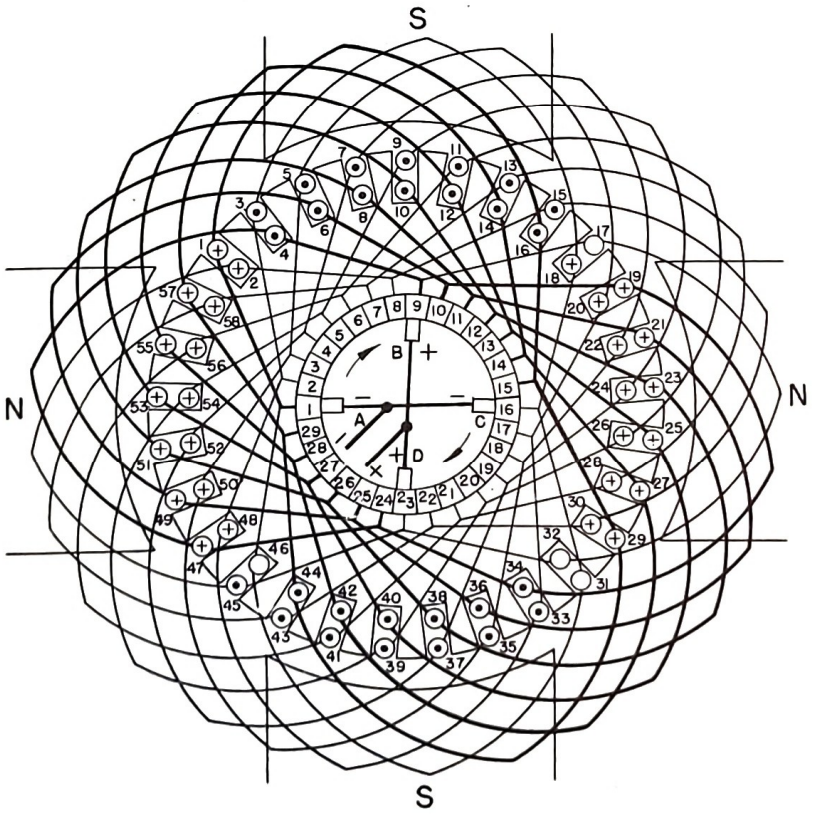


Fig. 26
A 29 slot, 4 pole retrogressive wave winding

It should be realized, however, that if two brushes are used instead of four, each brush must carry twice as much current, and so must have twice the cross section.

The thickness of a brush should not be increased, because it would short-circuit more coils. It must therefore be made wider, requiring a wider commutator and a longer motor. To avoid making the commutator wider, it is necessary to use the same number of brushes as there are poles.

There are a few cases in which the use of two brushes is a decided advantage. Good illustrations are crane and railway motors, in which access to the top and the bottom of the armature is difficult to provide.

POSITION OF BRUSHES IN A WAVE WINDING.- The wave windings considered are required in machines in which the brushes are in line with the pole centers, which is the most common condition. Regardless of where the brushes are situated, the coils must be connected to the commutator so that the coil voltages in each path will add, and so that the brushes will short-circuit coils only while they are not cutting flux, as explained in lap winding. If the brushes are in line with a point midway between the pole tips, the coils must be connected to the segments as shown in fig. 28.

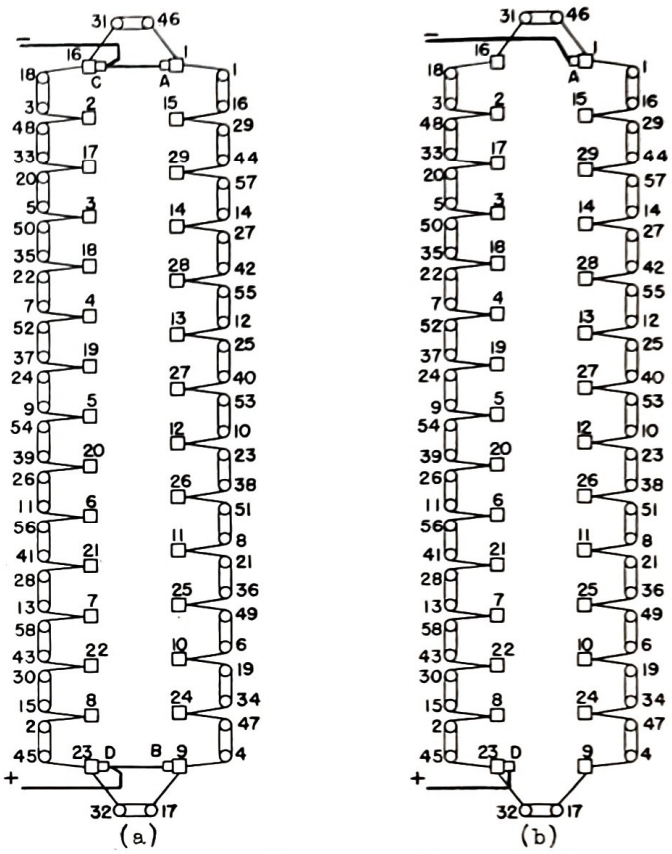


Fig. 27 Diagrammatic method of showing number of paths in the winding of fig. 26

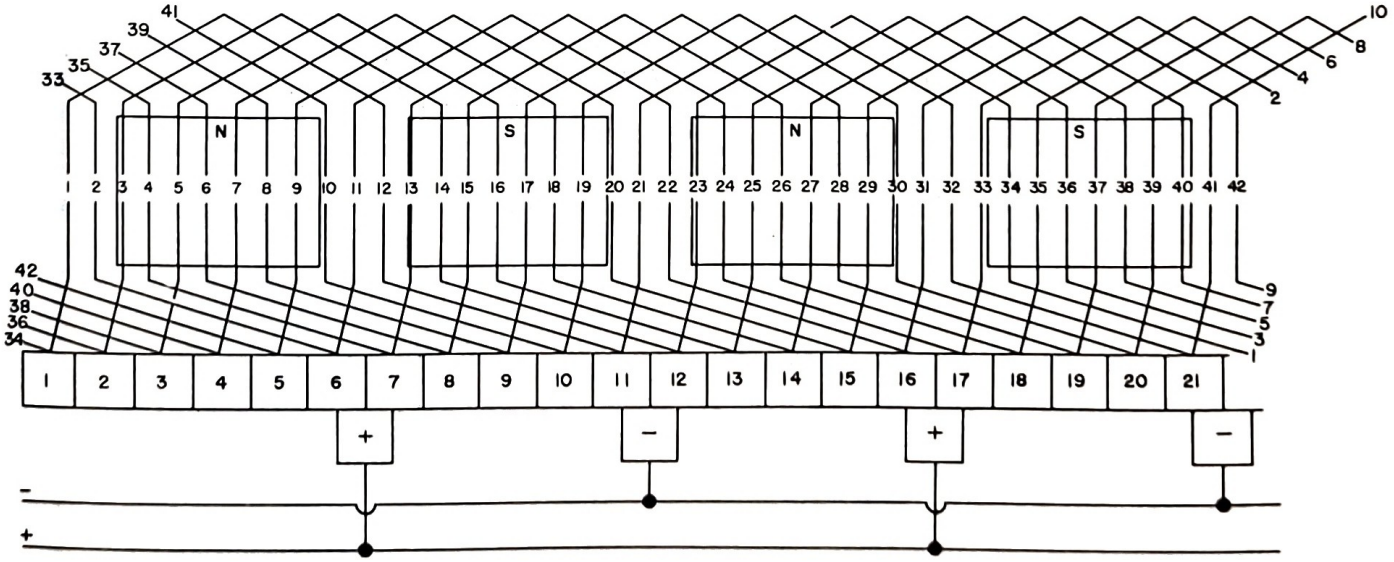


Fig. 28 Winding with brushes in line with a point midway between pole tips

1. How many paths has a simplex winding (a) with two poles? (b) with four poles? (c) with six poles?

2. (a) How many brushes are required in a wave winding? (b) Can any other number be used?

3. A 4 pole armature has 17 slots and 17 segments. If the armature is wound simplex wave, what is (a) the back pitch? (b) the commutator pitch? (c) the front pitch?

4. Make a wiring diagram of the armature in problem 3, placing the brushes in line with the pole centers.

5. A 6 pole, simplex wound armature supplies a current of 200 amperes. Determine (a) the current per path, and (b) the current per brush (state the number of brushes used.

6. A 6 pole, progressive simplex wave winding has 40 slots and 80 commutator segments. Determine (a) the back pitch, (b) the commutator pitch, and (c) the front pitch.

7. Show the connections of a few coils of the winding in problem 6, considering the brushes in line with a point midway between the pole tips.

8. A 6 pole, 6 volt, 50 kw duplex lap wound generator is reconnected simplex wave. Determine (a) the terminal voltage, and (b) the current at full load.

9. Using a cross section of 600 circular mils per ampere, what size wire is required for the armature of problem 8?

10. Make a schematic diagram of a 6 pole, simplex wave winding (show six brushes).

11. How far apart do the finish ends (or the start ends) of adjacent coils connect on the commutator for (a) a simplex winding? (b) a duplex winding? (c) a triplex winding?

DUMMY COILS.- Some armatures cannot be wave wound unless dummy coils are used. No dummy coils are needed if $2C \pm 2$ in equation 9 is a direct multiple of P. If it is not, the number of segments used must be reduced until it is a multiple. One dummy coil is required for each segment not used.

EXAMPLE.- A 4 pole, simplex wave wound armature has 22 slots and 22 segments. Determine the number of dummy coils required, if any.

$$y_c = \frac{2C \pm 2}{4} = \frac{2 \times 22 \pm 2}{4}$$

$$y_c = 10\frac{1}{2} \text{ or } 11\frac{1}{2}$$

Since the results are not whole numbers, the number of segments must be reduced. Considering 21 segments, then

$$y_c = \frac{2 \times 21 \pm 2}{4} = 10 \text{ or } 11$$

This means that the armature can be wound only if the number of segments and coils is reduced from 22 to 21. The coil to be omitted is inserted into the slots in the same way as the others, to make the armature dynamically balanced, but it is not connected to the commutator. Its ends are taped to insulate it from the rest of the winding. Since only 21 segments are required, two are connected together and considered as one.

This armature is shown in fig. 29.

MULTIPLEX COILS IN A WAVE WINDING.- A wave winding may have two or more times as many segments as slots, to keep the voltage between segments at a low value. The armature is then wound with multiple coils.

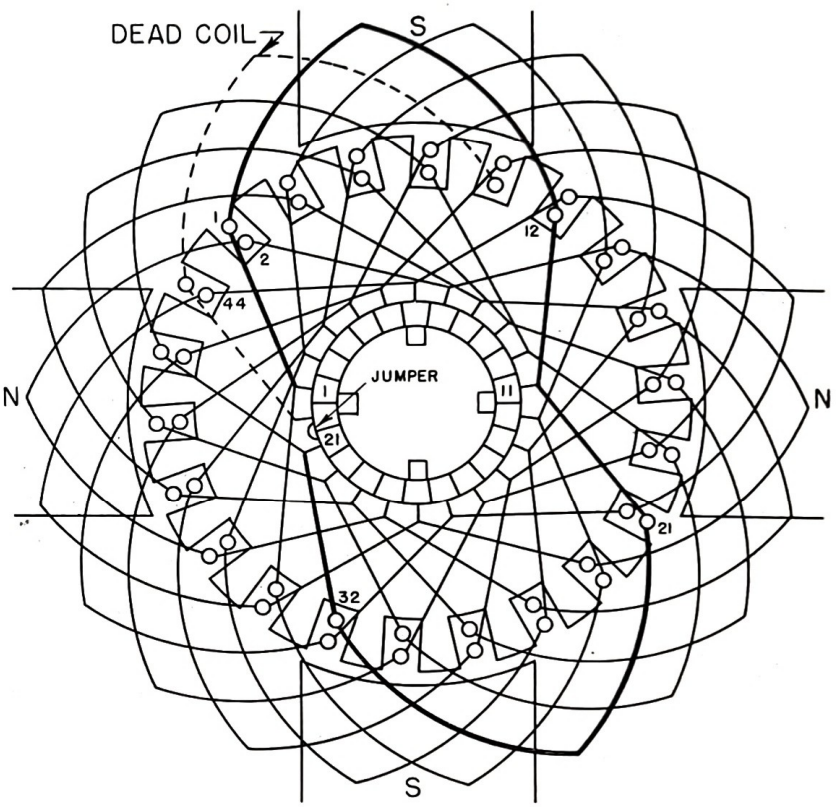


Fig. 29 A 22 slot armature with one dummy coil

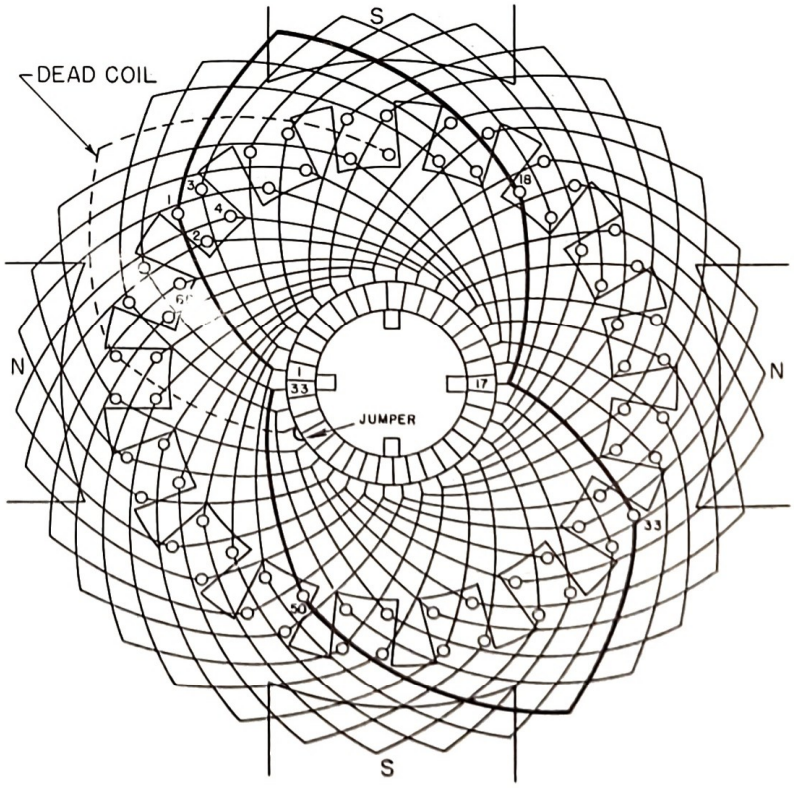


Fig. 30 A simplex wave winding which has twice as many segments as slots

EXAMPLE.- A 4 pole, simplex wave wound armature has 17 slots and 34 segments. Determine (a) the back pitch, (b) the commutator pitch, and (c) the front pitch.

(a) $C_s = \frac{2s}{S} = \frac{2 \times 34}{17} = 4$

$y_s = \frac{S}{P} = \frac{17}{4} = 4\frac{1}{4}$

Dropping the fraction,

$y_b = 4 \times 4 + 1 = 17$

(b) $y_c = \frac{2C - 2}{4} = \frac{2 \times 34 - 2}{4} = 16\frac{1}{2}$

Since the result is not a whole number, 33 segments will be considered.

$y_c = \frac{2 \times 33 - 2}{4} = 16$

(c) $y_f = 2y_c - y_b = 2 \times 16 - 17 = 15$

This winding is shown in the diagram of fig. 30.

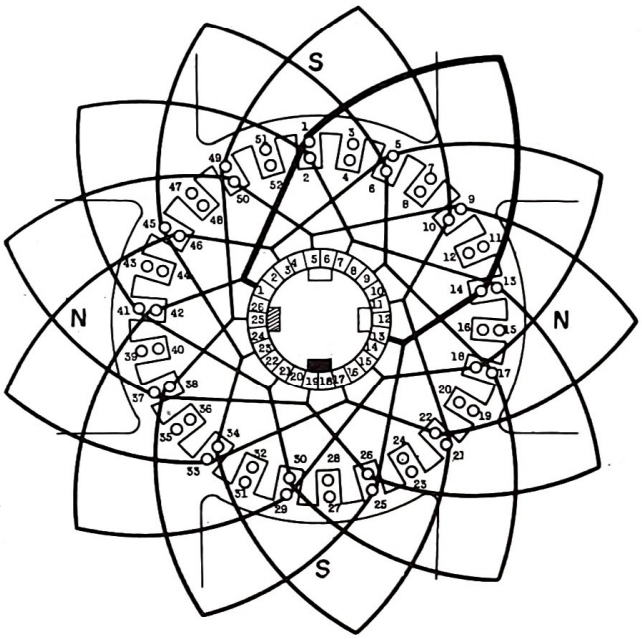


Fig. 31 A duplex, double reentrant wave winding (only one winding shown)

MULTIPLEX WAVE WINDING.- The definition given for multiplicity and reentrancy in lap winding (lesson 26) also applies for wave winding. That is, in wave winding, multiplicity refers to the number of independent windings while reentrancy refers to the separately closed windings on the armature.

Fig. 31 shows one winding of a duplex wound armature. On tracing once around the armature, the connection is made two segments from the starting point. In a triplex winding, the connection would be made three segments from the starting point.

Then for any multiplicity, equation 8 must be expressed as

$$y_{c\frac{P}{2}} = C \pm m$$

$$\text{or} \qquad y_c = \frac{2C \pm 2m}{P} \tag{12}$$

This applies to all wave windings. A multiplex winding will have no dummy coils only if $2C \pm 2m$ is a direct multiple of P.

PATHS IN A MULTIPLEX WAVE WINDING.- The number of paths in a multiplex wave winding depends on the multiplicity and not on the number of poles. It was shown that a simplex wave winding always has two paths. A duplex wave winding is merely two simplex wave windings in parallel, and therefore has four paths. A triplex wave winding has six paths, etc. Then for any multiplicity (m), the number of paths is

$$b = 2m \tag{13}$$

If the armature shown in fig. 31 has 24 slots and 24 segments, the winding would not fill the alternate slots and close, but would return to a segment to the left or the right of the one from which it started. In this case the winding will close only after the remaining alternate slots are filled. This is illustrated in fig. 32, in which one winding is shown dotted.

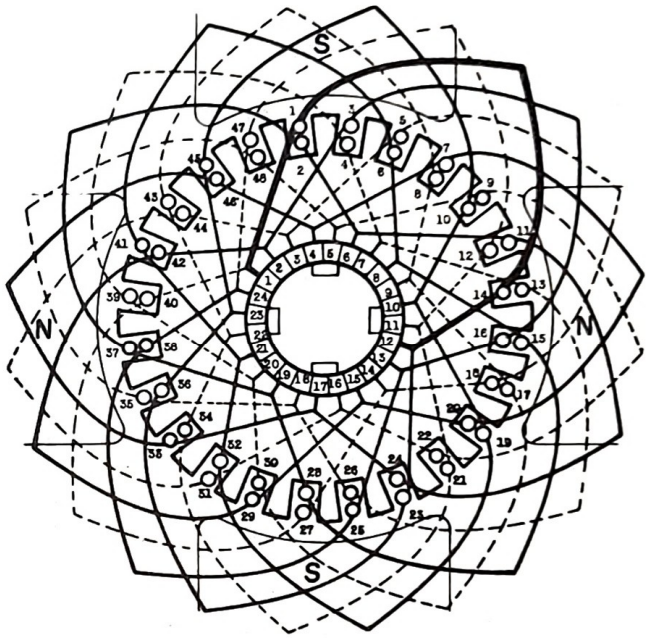


Fig. 32
Duplex wave winding (one winding shown dotted)

REENTRANCY IN A WAVE WINDING.- Fig. 33 shows a portion of a duplex wave winding, in which y_c is 20. In tracing through this winding it will be noted that it advances two segments each time it passes around the armature. If it arrives at 1, the winding will be double reentrant. If it skips segment 1, it will not close until a connection is made to all segments, in which case the winding will be single reentrant. To determine the degree of reentrancy in a wave winding, divide the commutator pitch by the multiplicity. If this gives a whole number, the winding is multiple reentrant; if this does not, it is single reentrant.

In wave winding, the finish ends of adjacent coils, and likewise the start ends of adjacent coils, connect to adjacent segments. Then the procedure for inserting coils and the method of connecting them in wave winding is the same as in lap winding (lesson 27 B).

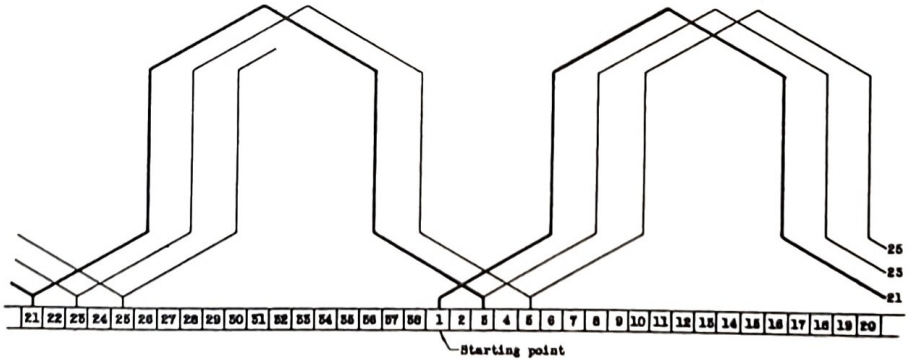


Fig. 33 Portion of a duplex wave winding

REQUIREMENTS FOR WAVE WINDING.- Three important requirements for wave winding may now be listed as follows:

(1) An armature can be wave wound, without dummy coils, if (2C ± 2m) is a direct multiple of P.
(2) The brushes must be wide enough to cover at least m segments.
(3) Two brushes are necessary, but as many brushes as there are poles may be used, and they must be set so that they short-circuit only the coils cutting no flux.

FROGLEG WINDING.- The frogleg winding consists of a lap winding and a wave winding placed in the same slots and connected to the same commutator segments. A part of a winding of this type is shown in fig. 34. The coils shown solid are a part of the lap winding and those shown dotted are a part of the wave winding.

This type of winding has the same industrial application as a lap winding with equalizers. The advantage of the frogleg type is that the wave winding serves as equalizer connections and also supplies voltage and current the same as a lap winding.

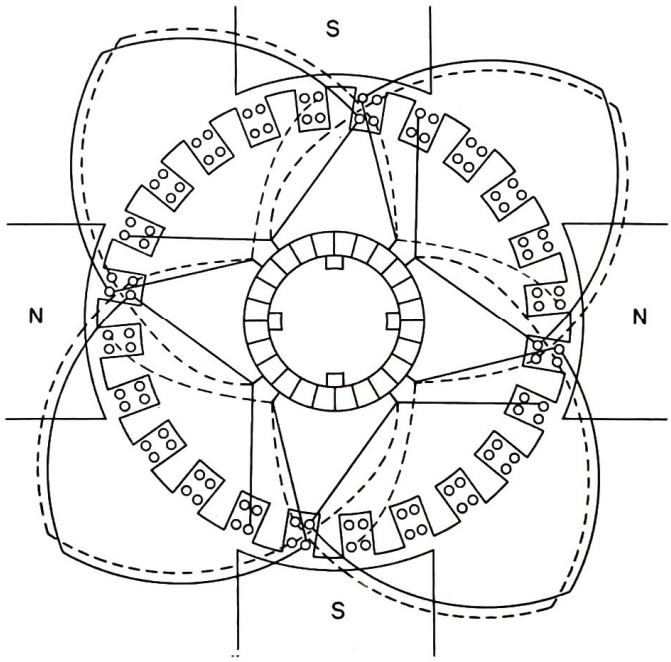


Fig. 34 Part of a frogleg winding

SELECTION OF TYPE OF WINDING.- If the current capacity of an armature is represented by I, the current per path or per conductor is I/b. The current per conductor fixes its size, because if less than a certain number of circular mils per ampere is used, the winding will overheat. In figuring an armature, if the size of wire determined is too large to be conveniently formed into a coil, a larger number of paths should be selected, so that the required size will be smaller. If the size determined is smaller than a size that can be conveniently formed into a coil, a smaller number of paths should be selected, so that fewer turns of larger wire will be required. Wire of larger size costs less per pound and requires less space for insulation. Also, in an armature with large size wire, the heat more readily leaves the copper, and therefore it operates at a lower temperature.

In general, a high current armature is lap wound to provide a large number of paths, and a low current armature is wave wound to provide a low number of paths. Usually 240 volt machines, up to about 75 horsepower, are simplex wave wound.

HOME WORK

1. Are dummy coils required (a) in some lap windings? (b) In some wave windings?
2. An 8 pole, simplex wave winding has 50 slots and 100 commutator segments. What is the minimum number of dummy coils such a winding may have?
3. How many paths has an (a) 8 pole, duplex wave winding? (b) A 6 pole, triplex wave winding?
4. An 8 pole armature has 42 slots and 126 segments. If it is wound triplex, determine (a) the back pitch; (b) the commutator pitch; (c) the number of dummy coils; (d) the front pitch; (e) the degree of reentrancy.
5. Can the armature in problem 4 be wound duplex?
6. What kind of machines are (a) lap wound? (b) wave wound?
7. How many paths has the winding shown in fig. 34 if it is completed?

GENERATED VOLTAGE.- The amount of e m f induced in a conductor depends upon the rate with which it is cutting flux. When a conductor cuts flux at the rate of 10^8 magnetic lines per second, one volt is induced in it. By utilizing this fact it is possible to determine the e m f generated in an armature.

Let E = generated voltage (that is, the voltage across the terminals of the generator at no load), P = number of poles, Φ = flux per pole, N = speed of the armature in revolutions per minute, b = number of paths, and Z = total number of conductors on the armature. Since there are two conductors per turn, the total number of conductors on an armature (Z) equals two times the product of the number of turns per coil (t_c) and the number of coils (C). Thus,

$$Z = 2t_cC \tag{14}$$

In one revolution each conductor cuts the flux per pole (Φ) times the number of poles (P), or $P\Phi$ lines. In one second the armature makes N/60 revolutions, and during this time each conductor cuts $P\Phi N/60$ lines. To obtain the average voltage induced in each conductor, this expression is divided by 10^8, giving

$$\frac{P\Phi N}{10^8 \times 60}$$

In an armature the total number of conductors (Z) is divided into b paths. The total generated voltage (E_g) equals the e m f generated in one path. The number of conductors per path is Z/b. Then the voltage per path is

$$\frac{Z}{b} + \frac{P\Phi N}{10^8 \times 60}$$

As the voltage per path is the same as the voltage at the terminals of the machine,

$$E_g = \frac{PZ\Phi N}{10^8 b60} \tag{15}$$

EXAMPLE 1.- Determine the voltage generated in a 6 pole machine, running at 900 r p m, if its armature is simplex lap wound and has 300 active conductors. The flux per pole is 5×10^6 magnetic lines. In this winding the number of paths equals the number of poles. Substituting in equation 15,

$$E_g = \frac{6 \times 300 \times 5 \times 10^6 \times 900}{10^8 \times 6 \times 60} = 225 \text{ volts}$$

EXAMPLE 2.- A 4 pole, 12 volt generator has a speed of 750 r p m. The flux per pole is 4×10^5 lines. If the armature is wound duplex lap and has 24 slots and 48 segments, find (a) number of coil sides per slot, and (b) number of turns per coil.

(a) $C_s = \frac{2s}{S} = \frac{2 \times 48}{24} = 4$

(b) Solving for Z in equation 15, $Z = \frac{10^8 b60E_g}{P\Phi N} = \frac{10^8 \times 8 \times 60 \times 12}{4 \times 4 \times 10^5 \times 750} = 480$ conductors

Solving for t_c in equation 14, $t_c = \frac{480}{2 \times 48} = 5$ turns per coil

1. How many coils has an armature with 34 slots and 68 segments?

2. How many conductors has a 20 coil armature if each coil contains 10 turns?

3. Determine the number of conductors on an armature which has 22 slots and 44 segments, if each coil has 4 turns?

4. A simplex winding on a two pole machine has 400 conductors. The flux per pole is 400,000 lines. What voltage is generated when the armature is running at 900 r p m?

5. An 8 pole generator, which runs at 850 r p m, has 10^6 magnetic lines per pole. How many conductors has the armature if it is wound duplex lap and supplies 240 volts?

6. If the armature in problem 5 has 21 slots and 21 segments, how many turns does each coil contain?

7. A 4 pole, duplex lap wound armature has 28 slots and 56 segments, and runs at 450 r p m. The flux per pole is 7×10^5 lines. If each coil contains 16 turns, what is the terminal voltage?

8. A 6 pole, 60 volt generator, which has a duplex lap wound armature, runs at 600 r p m. If the armature has 48 coils, how many turns does each coil contain?

9. A simplex wound armature of a two pole, 18 volt generator is wound with No. 12 wire, and the coils each contain 2 turns. If the armature is to be rewound for the same output and 120 volts, determine (a) the number of turns per coil, and (b) the size of the wire.

10. A duplex lap wound armature of a 4 pole generator delivers 100 amps at 12 volts. Each coil has 10 turns. (a) How many turns must each coil have if the armature is rewound simplex lap to generate 60 volts? (b) How much current will the armature deliver at full load?

11. A 120 volt, 6 pole generator has a triplex wave wound armature with 56 coils. Each coil has 4 turns and the flux per pole is 10^6 magnetic lines. If the generator is driven at 1800 r p m, determine the generated voltage.

12. The 4 poles of a generator are each 8 square inches in cross section and have a flux density of 60,000 magnetic lines. The armature has 36 slots and 102 segments. If the armature is wound triplex lap and generates 240 volts, determine the turns per coil.

WINDING SMALL ARMATURES.- Form wound coils are seldom used on small armatures, the coils being generally wound directly on the core by hand or machine. Machine winding is preferable, because the armature can be wound much faster. The coils may be wound on the core in many different ways, but they are always connected to the commutator as explained in lap and wave winding. Methods of winding the coils, and not methods of connecting them to the commutator, will therefore be discussed.

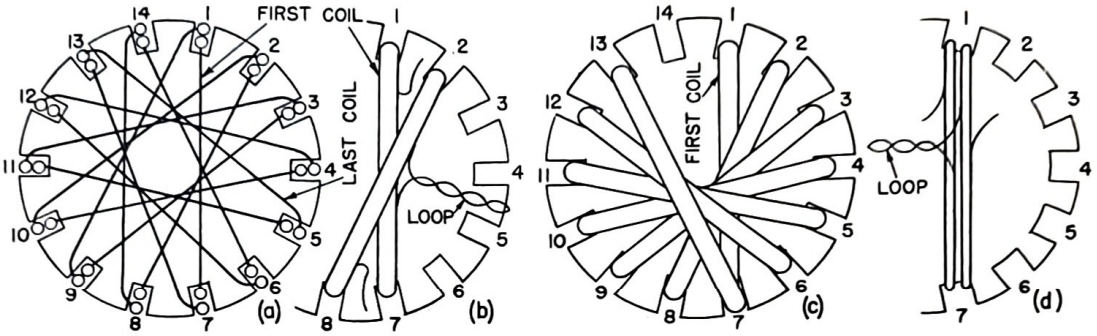


Fig. 45 Loop wound armature

LOOP WINDING.- A type of winding much used on small cores, known as loop winding, is shown in fig. 45a. For this winding, the armature must have the same number of bars as slots. After the first coil is wound, a loop is made, and then the next coil is started in the second slot (see fig. 45b). This is continued (see fig. 45c) until all the coils are wound.

If the armature has twice as many commutator segments as slots, the second coil is wound in the same slots as the first, with a loop between the two (see fig. 45d). The third is started in slot number two and the process is repeated. For a simplex winding the loops are connected to adjacent commutator segments.

This winding can be placed on a core with any number of slots. It is easily wound, either by hand or by machine. Its coils are not all alike, and consequently it is not electrically or mechanically balanced.

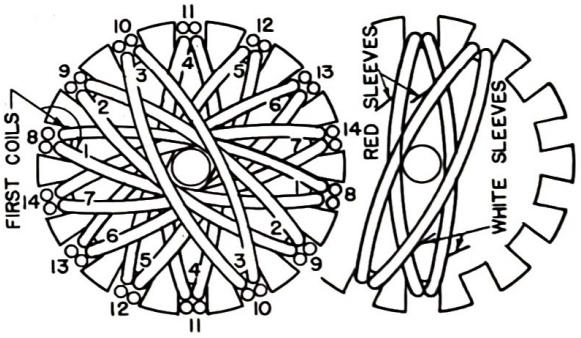


Fig. 46 Split winding

FULL PITCH SPLIT WINDING.- In a full pitch split winding, which is shown in fig. 46a, the number of slots must be even. Half of each coil is wound on one side of the shaft and the other half on the other side. The procedure in winding the coils is shown in fig. 46b. Sleeves should be used to indicate the start and finish ends.

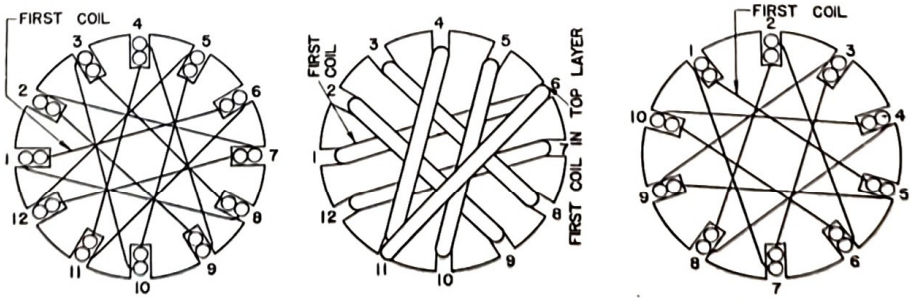


Fig. 47 Fractional pitch split loop winding

The second coil is started in the second slot, the third coil in the third slot, etc. After half the coils are wound, the bottom layer is complete. The top layer is started in the same slot as the finish end of the first coil, so that after the armature is wound, a start end and a finish end protrude from each slot.

This type of winding is most suitable for an armature with coils that require a few turns of heavy wire. It is recommended for machines that have little winding space at the ends.

FRACTIONAL PITCH SPLIT WINDING.- The coils in this type of winding, which is shown in fig. 47a, also require sleeves to distinguish the start from the finish ends. One coil is wound, and the armature is then turned 180 degrees and the next coil is started. The third coil is started in the third slot beyond the finish end of the second coil. After the third coil is wound, the armature is again turned 180 degrees and the next coil is started, etc.

The top layer is started in the second slot beyond the finish end of the last coil on the bottom layer (fig. 47b). To wind the remaining coils, the same scheme is used that was used in winding the bottom layer.

After all the coils are wound, it will be noted that each slot contains a start end and a finish end. In this winding, and also in the full pitch split winding, the last two coils are tied together to keep them from flying outward when the armature is rotating.

If the number of slots is not divisible by four but is divisible by two, the same general procedure is used; that is, the coils are wound on the core in pairs, proceeding in the clockwise direction until all are wound. Such a winding is shown in fig. 47c.

The advantage of split winding is that it gives a better mechanical and electrical balance than loop winding.

V WINDING.- A few steps in inserting the coils in the V winding shown in fig. 48a are illustrated in fig. 48b. The first coil will lie at the bottom of the slots. The following coils, except the last, will have one side at the bottom of a slot and the other side at the top of another slot. The last coil will have both sides at the top of slots. To eliminate complications which may arise when making commutator connections, sleeves should be used.

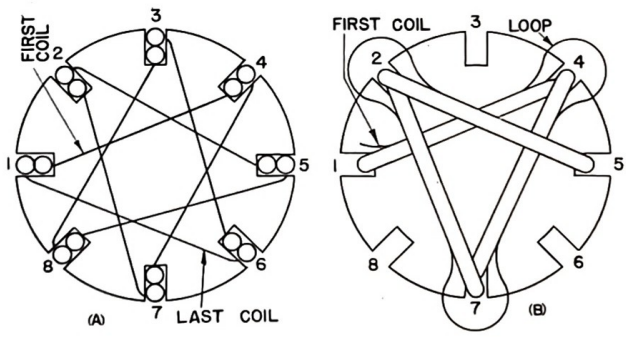


Fig. 48 V winding

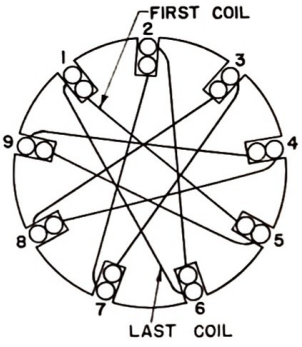


Fig. 49 V winding

A distinctive feature of this winding is that the slots are filled as the winding progresses.

The variation in coil lengths in this winding is about the same as in the split winding. Its advantage over the split winding is that it can be wound on a core with any number of slots. In fig. 48a is shown a winding with an even number of slots; in fig. 49 is shown one with an odd number.

ARMATURE TESTING.- A method commonly used for testing armatures for short circuits and open circuits is known as the segment to segment test. This test may be made on an armature with any type of winding. The method of testing a simplex lap wound armature is illustrated in fig. 50a. A low D C voltage is impressed between two points diametrically opposite on the commutator.

Voltage measurements are made between adjacent commutator segments. To facilitate making these readings rapidly, the terminals of the voltmeter are clamped close together by means of two non-conducting strips. Generally the voltage supplied must be adjusted so that the meter will indicate at some convenient value on the scale. If the armature has no faults, like readings will be obtained between any two commutator segments. If little or no reading is obtained when the voltmeter terminals are placed on adjacent segments, a coil between these segments or the segments themselves are short-circuited. If zero readings are obtained between segments connected to coils in one path, except between two segments where the reading is high, the winding is open between these segments (see fig. 50b)

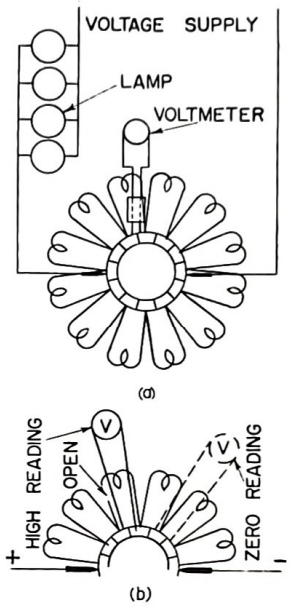


Fig. 50
Armature testing outfit

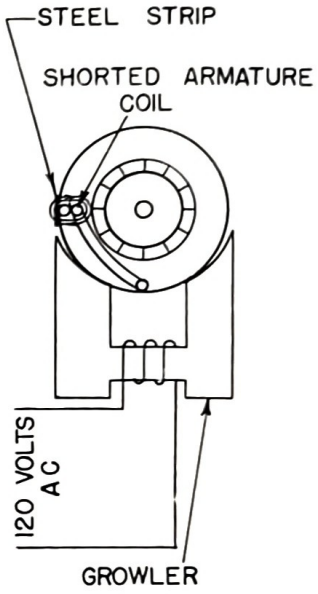


Fig. 51
Growler test

GROWLER TEST.- A coil with a few short-circuited turns cannot always be located by employing the segment to segment test. In this case the short circuit is located by means of a device commonly called a growler (so-named because of the growling noise it makes). Such a device is shown in fig. 51. When a growler is energized with alternating current, an expanding and contracting flux is established, which induces a voltage in the armature winding. If the winding has no faults, no current will flow in the armature coils. If a coil is short-circuited, a current will flow in the short-circuited turns. To locate the faulty coils, a steel strip such as a hacksaw blade is passed over the slots, so that when a coil side lies under the blade, the other coil side of the same coil lies between the pole faces of the growler. When one coil side of a short-circuited coil lies under a blade, the current in this coil sets up a flux which attracts the blade. If a part of the blade is held slightly away from the core, the blade will vibrate, making a noise, which indicates a short circuit.

HOME WORK

1. Give the advantages and disadvantages of winding the coils directly on the core instead of using form wound coils.

2. Make wiring diagrams of two pole, 8 slot armatures which are (a) loop wound; (b) full pitch split wound; (c) fractional pitch split wound; (d) V wound. Indicate the first and last coil in each.

3. Which windings stated in problem 2 can be placed on cores with any number of slots? Each of the other windings requires how many slots?

4. What is the chief undesirable feature of the full pitch split winding?

5. How are armature windings tested for short circuits and open circuits?

A modern D.C. generator with the main parts named is shown in fig. 1. These parts will be discussed in detail below.

ARMATURE.- The armature core is made of soft iron or mild steel stamping about 0.025 inch thick (fig. 2a). The core is laminated to cut down eddy currents, which would otherwise be excessive. In small machines these laminations are keyed directly to the armature shaft, while in large ones they are keyed to the spider, which in turn is keyed to the shaft. The slots of the armature core are first lined with fish paper then the coils are inserted into the slots. The coils are usually held in place by wooden or fiber wedges driven into the top of the slots. The sections of the coils not in the slots are held in place by band wires.

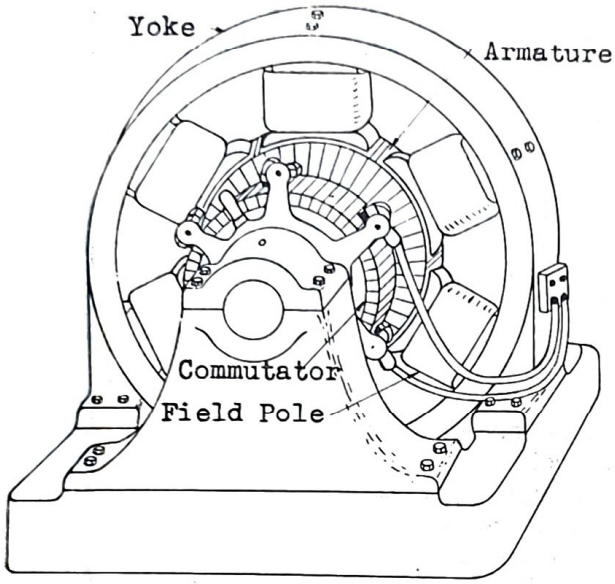
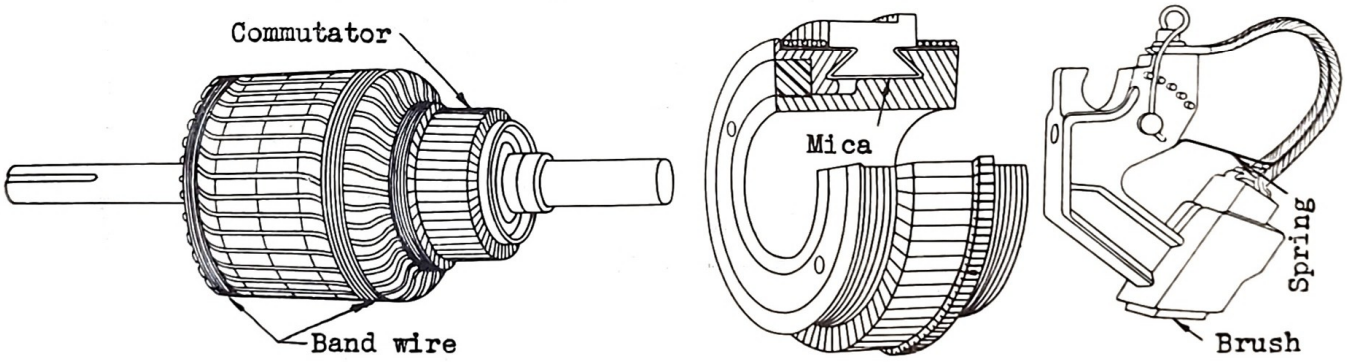


Fig. 1 D.C. generator.

The commutator is made up of copper segments insulated from the supporting rings by mica cones (fig. 2b). These segments are held firmly in place by wedged shape clamping rings drawn together by bolts in large machines and by a nut on the shaft in small machines. The leads from the armature coils are soldered into slits or into risers located at the ends of the segments.



(a) Armature (b) Commutator (c) Brush and brush holder.

Fig. 2 The main parts of the armature with brush and holder.

BRUSHES.- The purpose of brushes (fig. 2c) is to carry current from the commutator to the external circuit. They are usually made of blocks of graphite carbon, although in very low voltage machines brushes of copper gauze or metal patent compounds are sometimes used. The brushes should slide freely in their holder so as to follow any irregularity in the commutator. The brushes should bear upon the commutator with a pressure of about 1.5 lbs. per square inch of contact area. A suitable spring is provided on the brush holder to adjust the brush tension. To decrease the brush resistance the upper portion of the brush is copper-plated. This plating is connected to the brush holder by a pigtail made of twisted copper wire.

FRAME.- The frame or yoke of a generator serves as a mechanical support for the machine and forms a part of the magnetic circuit connecting the field poles. In small machines, where weight is of little importance, the frame is made of cast iron and the feet form a part of the casting (fig. 3). In another type of construction the frame is made of a steel plate which has been rolled into a ring and then welded. The feet are then welded to this ring.

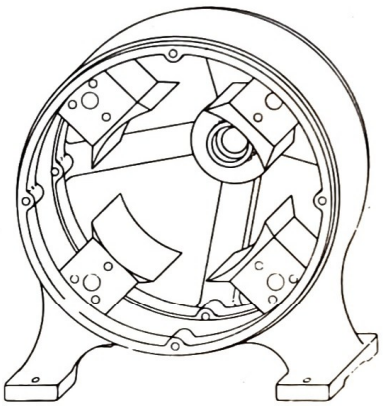


Fig. 3
Frame of a D C generator

FIELD CORES AND SHOES.- Field cores are made of cast steel, forged steel, or steel laminations. When cast or forged steel is used, the cores are usually made circular in cross section. Laminated cores, which are used almost universally except on very small machines, have a rectangular cross section and are held to the frame by bolts.

FIELD EXCITATION.- In all generators, except in very small ones called magnetos, the field flux is produced by current flowing in coils placed on the pole pieces. The e m f required to force current through the field coils may be obtained either from a separate source, such as another generator, or from the armature of the generator itself. When the field is excited from a separate source the machine is said to be separately-excited, and when the current is obtained from its own armature it is said to be self-excited. Self-excitation may be obtained in three ways--by shunt excitation, series excitation, or compound excitation.

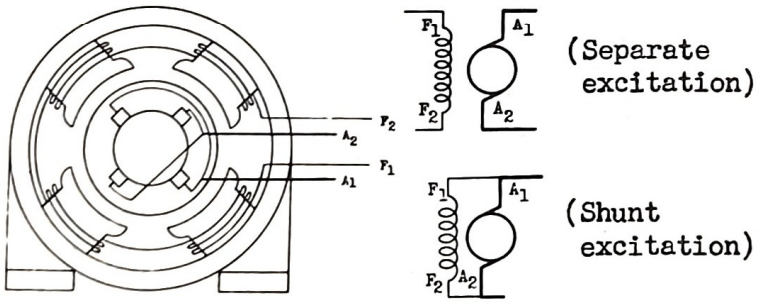


Fig. 4 Separate and shunt excited generator

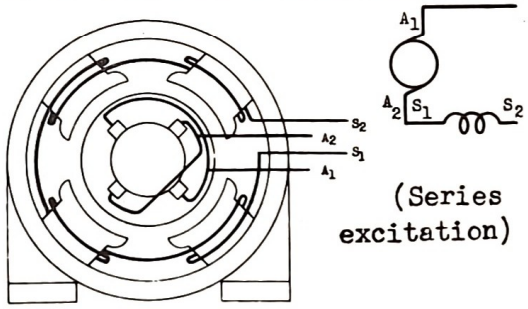


Fig. 5 Series excited generator

In machines designed for either separate or shunt excitation (fig. 4), the field coils are made of a large number of turns of relatively small wire, thus providing a high resistance and taking a small current. A rheostat is usually included in the field circuit to vary the generated voltage.

In machines designed for series excitation, the field coils are made of a few turns of large wire, because these coils carry the total current of the machine (fig. 5).

A generator designed for compound excitation has both a shunt and a series winding placed on the field poles (fig. 6a). Ordinarily the series coils are connected to aid the shunt coils, and the machine is said to be cumulatively compounded. Sometimes the series winding is connected to oppose the shunt, or the machine is differentially compounded. A compound machine is long shunted when the shunt field is connected directly to the line (fig. 6b).

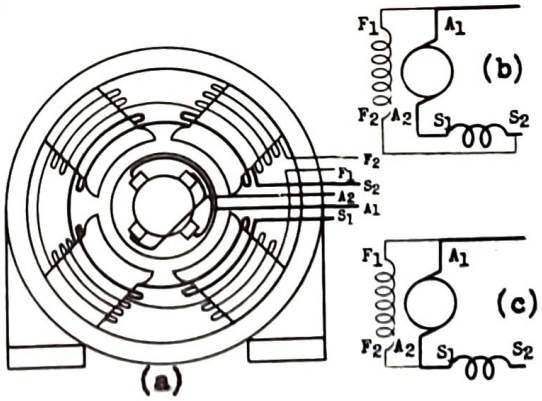


Fig. 6 Compound generator

When connected directly to the brushes (inside the series field), it is short shunt (fig. 6c). There is very little difference between the two connections. The various methods of connecting the field coils to meet certain operating requirements will be made clear in the discussion of external characteristics.

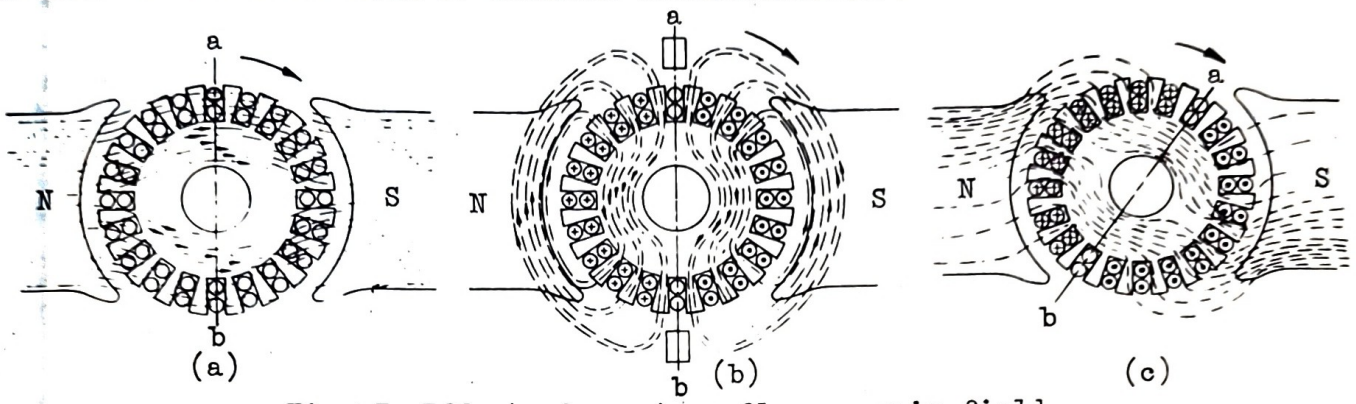


Fig. 7 Effect of armature flux on main field

ARMATURE REACTION.- Fig. 7a shows the magnetic flux set up in a generator when the armature is supplying no current to an external load. This flux is produced entirely by the ampere-turns of the field. The neutral plane (a plane perpendicular to the flux) is represented by the line 'ab'. This line is said to coincide with the mechanical neutral of the machine.

In fig. 7b the main field excitation has been removed, but the armature conductors are carrying current in the direction they would be carrying it if the generator were carrying a load. The conductors to the left of the neutral plane carry current away from the observer. The m m f's produced by these conductors combine and send current downward through the armature, this direction being determined by the thumb rule. Conductors to the right of the neutral plane carry current toward the observer. Their combined m m f's also send flux downward through the armature. Thus the m m f's produced by the conductors on both sides of the neutral plane combine and send flux downward through the armature, in a direction at right angles to the field axis.

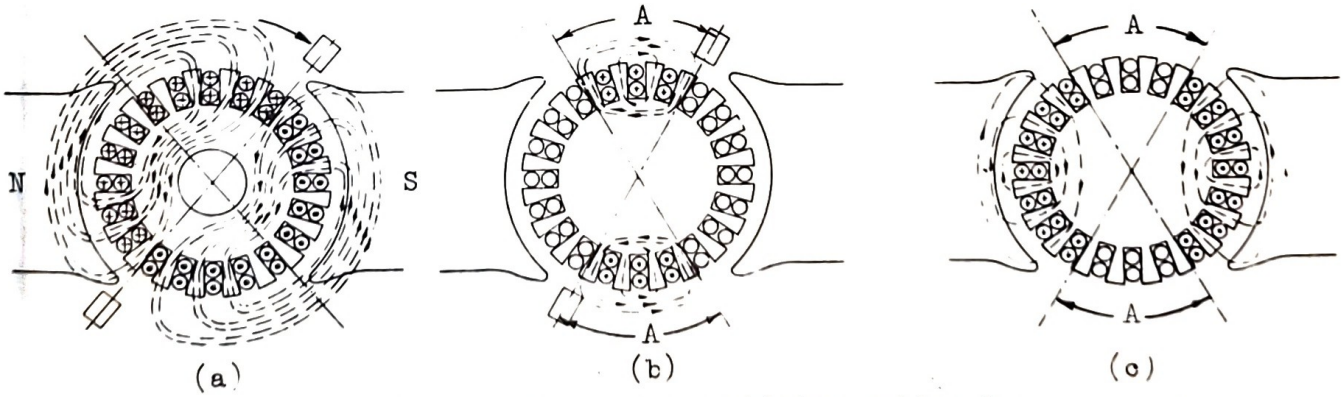


Fig. 8 Demagnetizing and cross-magnetizing action in a generator

Fig. 7c shows the result obtained in a loaded generator when current flows through both the armature and the field windings. At the upper tip on the north pole, and at the lower tip on the south pole, the armature and the main flux are in the same direction, hence the resulting flux is greater than it would be if there were no armature current. At the lower tip of the north pole and the upper tip of the south pole, the armature and the field fluxes are in opposition, so that the resulting flux is equal to the difference of the two. Hence these two tips have a lower flux density.

As a result, the main flux is distorted in the direction of armature rotation. It should be borne firmly in mind that the flux is not distorted by the mechanical rotation of the armature. Since the neutral plane is always perpendicular to the resultant field, it has now advanced in the clockwise direction from the position shown in fig. 7b to the position in fig. 7c.

It was explained in armature winding that the brushes must be set so as to short circuit a coil only while it is passing through the neutral plane (it will be shown later that the brushes should short circuit the coil undergoing commutation a little ahead of the neutral plane). If the brushes are advanced to the new position of the neutral plane, all the conductors to the left of the two brushes carry current away from the observer, while those to the right carry current toward the observer (fig. 8a). This shifting of brushes causes the neutral plane produced by the armature and field flux to shift still further from the vertical position. The net result is that the resultant field tends to skew more and more as the brushes are shifted toward the neutral plane. Fortunately, however, the piling up of the flux in the pole tips saturates them, so that the brushes may be shifted even past the neutral plane.

Then entire armature winding of fig. 8a may be considered to be made up of two distinct groups of conductors--those within angles A (fig. 8b) and those outside angles A (fig. 8c). The turns formed by the conductors within angles A produce a flux, which opposes and thereby reduces the main field flux through the armature. For this reason these turns are called demagnetizing ampere-turns. Since the magnetizing effect increases with an increase in brush shift, the brushes should be set as close as possible to the mechanical neutral plane. The turns formed by the conductors outside angles A send a flux downward through the armature. For this reason these turns are called cross-magnetizing ampere-turns. The flux produced by these turns distorts the main flux and produces a strong and a weak tip on each pole. The combined effect of the demagnetizing and cross-magnetizing ampere-turns is called armature reaction. Armature reaction may be reduced by increasing the length of the air gap, but this increases the reluctance of the path of the combined armature and field flux, and therefore an increase in field ampere-turns is required. Armature teeth designed to carry a high flux density also reduce the effect of armature reaction.

HOME WORK

1. What is a suitable brush tension in a D C machine?

2. What is the purpose of a field rheostat?

3. Why are the field poles and armature of a direct current machine laminated?

4. Explain the ways in which the armature winding is held in the slots.

5. Explain the difference between the mechanical neutral plane and the electrical neutral plane.

6. How does a series generator differ in construction from a shunt generator?

7. What are the detrimental results of armature reaction in a generator?

8. Name the different types of direct current generators.

ARMATURE REACTION IN MULTIPOLAR MACHINES.- In multipolar machines, armature reaction occurs in the same manner as in the bipolar machines described above. However, the diagram may appear slightly different. In fig. 9, a section of the armature and two field poles of a multipolar machine are shown, the armature being shown as a flat surface for convenience.

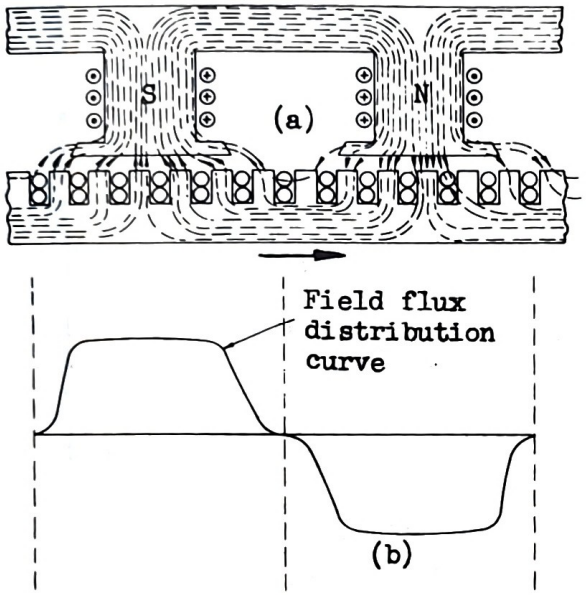


Fig. 9 Flux distribution due to field current only.

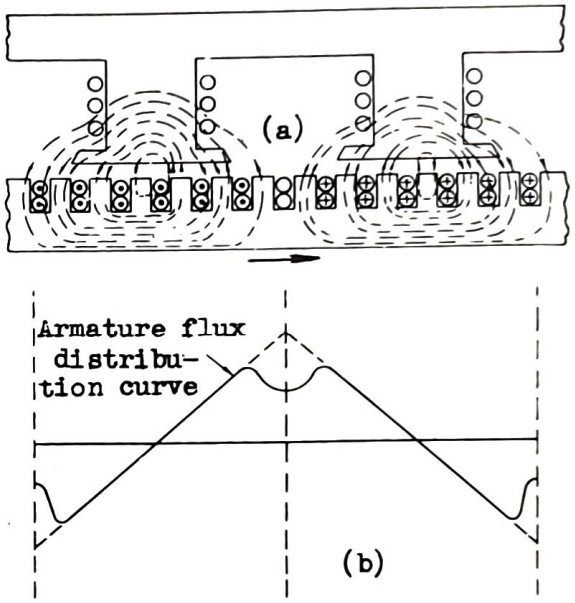


Fig. 10 Flux distribution due to armature current only.

Fig. 9a, shows the distribution of the magnetic lines between two poles when current flows through the field winding only. The density of these lines at the surface of the armature is maximum under the central portion of each pole and decreases gradually toward the pole tips, then decreases rapidly beyond the pole tips, becoming zero midway between the poles. Although fig. 9a shows clearly the distribution of the lines of force in a section of the machine, the distribution of the useful flux at the surface of the armature may be more conveniently represented by a flux distribution curve as that shown in fig. 9b. In this curve note that the

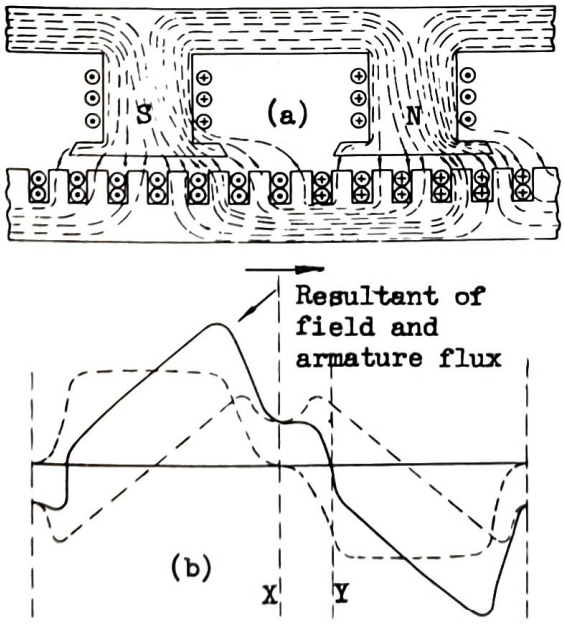


Fig. 11 Flux distribution due to the combined action of field and armature current.

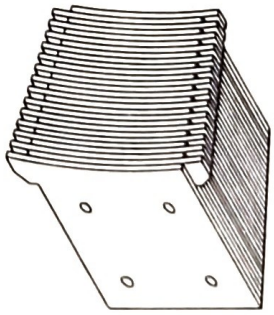


Fig. 12 Field pole laminations assembled.

flux is substantially constant under the pole shoe, falls to zero at the neutral plane, and extends in the opposite direction under the next pole.

The magnetic field set up by the armature current when the brushes are in the mechanical neutral plane is shown in fig. 10a. The corresponding flux distribution curve is shown in fig. 10b. The conductors between 'a' and 'b' may be thought of as forming a pancake coil with center under the brush located between these two poles. If it were not for the relatively large air-space between poles, the flux distribution curve would be as indicated by the dotted lines (fig. 10b). However, the actual distribution is indicated by the solid line curve. Note that the maximum flux is under each pole tip.

The resultant flux distribution due to the combined action of the field and armature current is shown in fig. 11a (in this figure it is assumed that the iron has a constant permeability). By adding the flux curves of figs. 9b and 10b, the resultant distribution curve is obtained; this curve is shown in fig. 11b. It will be noted that the flux is distorted in the direction of rotation as in bipolar machines and that the neutral plane is shifted from XX to YY.

COMPENSATING ARMATURE REACTION.- Since the cross-magnetizing effect of the armature makes it necessary to shift the brushes with the load, it is often desirable to minimize the cross-magnetizing effect produced by the armature. One method of doing this is to build field poles of laminations having only one tip as shown in fig. 12. These, when stacked, are alternately reversed so as to leave space between laminations at the pole tips. The small cross-section of iron at the pole tips becomes saturated and thus the permeability is reduced. This has the effect of reducing flux distortion.

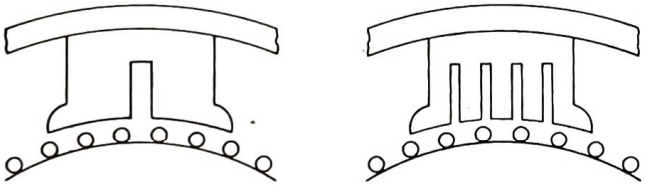


Fig. 13 Laminations provided with slots so as to reduce cross-flux.

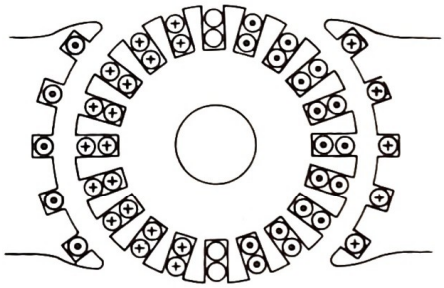


Fig. 14 A winding provided to neutralize the effect of the armature flux.

Another method of reducing the effect of the cross-flux is to place one or more slots in the pole face as shown in fig. 13. These slots produce a high reluctance for the armature flux, but have little effect on the field flux.

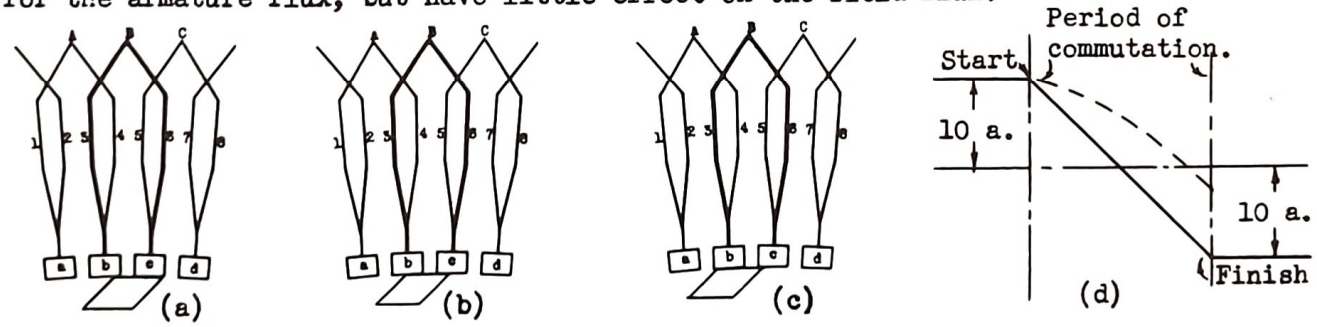


Fig. 15 The commutation process.

The magnetizing effect of the armature may be neutralized by means of a compensating winding embedded in the pole faces as shown in fig. 14. These pole-face conductors are connected in series with the armature so as to carry the same current as the armature, but the connection is so made that every conductor embedded in the field poles carries current in the opposite direction to that of the adjacent conductor on the armature.

Compensating windings are not used on many machines, because of the cost of manufacturing them. Their greatest uses are on high speed and high voltage generators of large capacity.

COMMUTATION.- It was shown in lesson 25 that the current through a coil, rotating in a magnetic field, reverses as the commutator segments to which the coil ends are attached pass under the brush. The commutator serves also to maintain the current in one direction through the external circuit. The process of conducting the current from the coils to the brushes is shown in fig. 15 and is called commutation. In fig. 15a commutation of coil B has just started, because the brush is just beginning to make contact with segment 'b'. Before this occurred, coil B was carrying the same current as all the other coils to the left of the brush. Assume this current to be 10 amperes. As soon as segment 'b' makes contact with the brush, coil B is short-circuited, and the current in this coil begins to change. Under ideal conditions, the current in coil B should decrease at a uniform rate until the coil is midway in the period of commutation. At this point the current should be zero (fig. 15b). The current should then increase in the reverse direction at a uniform rate until segment 'c' is ready to break contact with the brush (fig. 15c). Now coil B is about to be cut into the armature circuit on the opposite side of the brush and must have 10 amperes flowing through it in the opposite direction. The current change in coil B under these ideal conditions is shown by the solid line in fig. 15d. The requirement for ideal commutation is that the coil, after being short-circuited by the brush, must have its current completely reversed and brought up to the initial value before it is again cut into the circuit. Then no current flows from segment 'c' to the brush at the instant it breaks contact. If current is flowing between the brush and the segment when this break occurs, there will be sparking.

Securing the ideal conditions illustrated in fig. 15d was one of the outstanding difficulties in the early development of electrical machinery. In a coil undergoing commutation, it is difficult to reduce the current to zero and build it up to an equal value in the opposite direction during the brief interval that the coil is short-circuited by the brush. This difficulty exists because self-inductance prevents the current from changing rapidly. This results in coil B moving into the circuit to the right before the current has completely reversed and built up to 10 amperes. This condition is shown by the dotted line in fig. 15d. Note that the current must rise suddenly to 10 amperes when the break occurs, which causes sparking.

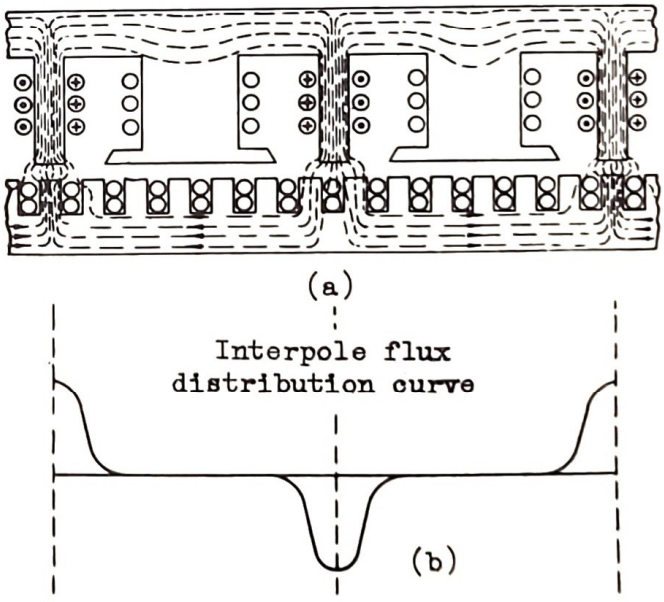


Fig. 16 Flux distribution due to the use of commutating poles

The early methods employed to eliminate sparking consisted of shifting the brushes (in the direction of rotation of the armature, in the case of a generator) until the coil was cutting a small amount of flux from the oncoming main poles. The induced voltage decreases the coil current to zero and builds it up to the desired value in the opposite direction. This method is successful under steady load conditions, but, unfortunately, the strength of the required reversing field varies with the amount of current to be reversed, so that variable load conditions necessitate frequent shifting of brushes. Attempts have been made to use mechanical brush shifters actuated by solenoids in series with the armature, but these were not entirely satisfactory.

An important step was made when carbon brushes were substituted for the copper brushes first used. Having comparatively high contact resistance, carbon assists in throttling the current in the coil undergoing commutation. The use of carbon brushes in conjunction with brush shifting was standardized for a considerable period. The degree of shift was that required under average load conditions.

COMMUTATING POLES.- It was explained above that the voltage required to overcome the self-induced e m f in the short-circuited coil may be secured by shifting the brushes in the direction of rotation of the generator. Another way of securing the same effect is to leave the brushes in the mechanical neutral and to produce at this point the required commutating flux. This is accomplished by means of auxiliary poles called commutating poles or interpoles. These are placed midway between the main poles, as shown in fig. 16a. Interpoles are much narrower than the main poles and set up a flux in the proper direction and of sufficient magnitude to produce satisfactory commutation. The distribution of this commutating flux is shown by a curve in fig. 16b.

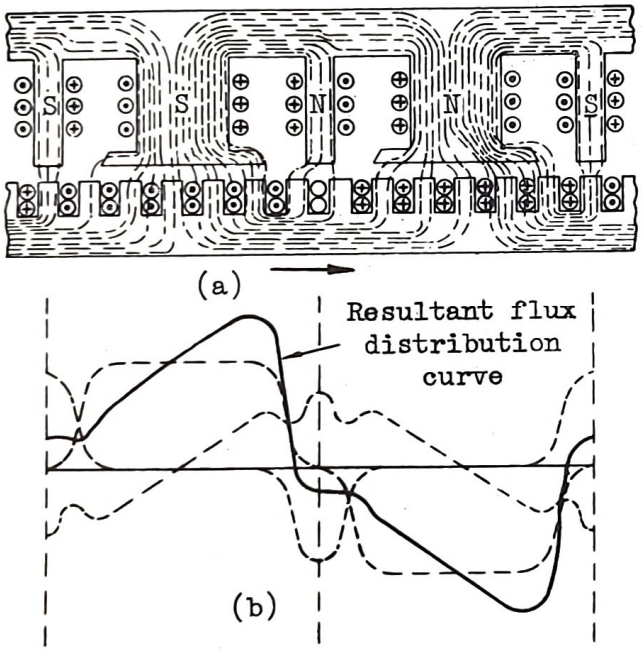


Fig. 17 Resultant flux distribution

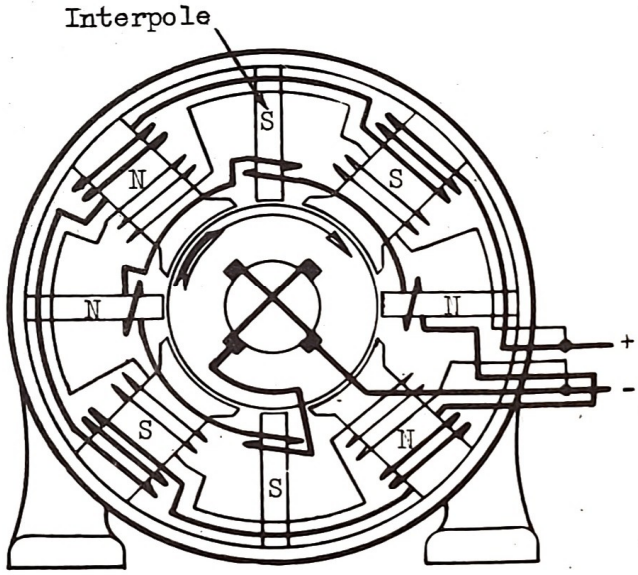


Fig. 18
D C generator with interpoles

The resultant magnetic field in the air gap is then made up of three magnetic fields, namely, one due to the field current (fig. 9b), another due to the armature current (fig. 10b), and still another due to the current in the commutating winding (fig. 16b). The curves for these three fields and the resultant curve are shown in fig. 17b. In this figure it should be observed that the interpole flux neutralizes not only the field in the neutral plane due to armature reaction, but also produces the proper flux to generate an e m f in the short-circuited coil, equal and opposite to the e m f of self-inductance. This produces an ideal condition for commutation. Since armature reaction and the e m f due to self-inductance in the armature undergoing commutation are both proportional to the armature current, then the flux produced by the commutating poles must likewise be proportional to the armature current. This proportionality may be obtained by connecting the interpole winding in series with the armature, as shown in fig. 18. It should be noted that the coils of the interpoles are so connected to the brushes as to cause the commutating poles to have the same polarity as the main poles directly ahead of them.

THE SATURATION CURVE.- Suppose that equation 15 in lesson 30 is written as

$$E_g = \left(\frac{PZ}{60b10^8}\right)\Phi N \qquad (1)$$

For any generator the quantity within the parenthesis is constant, and may be indicated by K. Then

$$E_g = K\Phi N \qquad (2)$$

This shows that the generated e m f in a machine is directly proportional to the flux per pole and the speed. Consider the speed kept constant. Then the generated e m f is directly proportional to the flux. The flux is produced by the field ampere-turns, but as the turns remain constant, the flux depends upon the field current. It does not vary directly as the field current, however, because of the varying reluctance of the magnetic circuit. The curve in fig. 19a shows how the flux per pole varies with the field current. Due to residual magnetism, the curved part at 'a' does not start at zero but at some value slightly greater. Beyond this part the curve to 'b' is practically straight because the flux increases in proportion to the field current. At 'b' the line begins to curve, for the magnetic circuit is becoming saturated.

Equation 2 shows that the generated e m f varies directly with the field flux. Hence, the generated e m f curve is the same as the flux curve, as shown in fig. 19b. Because the field poles become saturated, the voltage beyond 'b' increases rapidly with a given change in field current. Shunt generators are designed to operate at a point slightly above 'b' so that a slight change in speed produces an unnoticeable change in generated e m f. Compound generators are designed to operate slightly below 'b' so that a few series field ampere-turns give the desired increase in voltage.

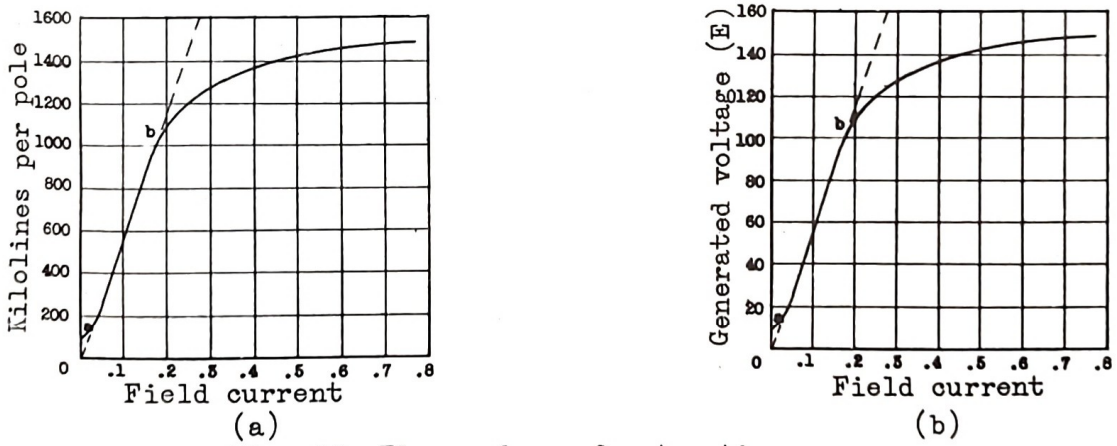


Fig. 19 Flux and e m f saturation curves

SEPARATELY EXCITED GENERATOR.- Suppose this type of generator is operated at a constant speed and with a constant field excitation. When it is unloaded, the terminal voltage will equal the generated e m f. When it is delivering current, the terminal voltage will be less than the generated voltage. This voltage decrease is due to two reasons. (1) As the flux per pole is reduced by the armature reaction, the e m f generated by cutting this flux is also reduced (shown by curve 'a' in fig. 20). (2) The terminal voltage becomes less than the generated e m f by an amount equal to the IR drop of the armature winding and the brushes.

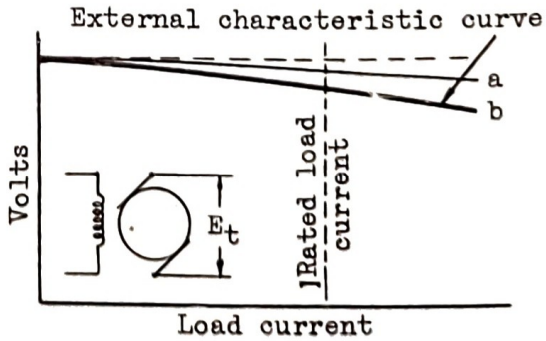


Fig. 20 Characteristic curves of the separately excited generator

This drop is indicated by curve 'b', which is known as the external characteristic curve of the separately excited generator.

In practice the terminal voltage of a machine is controlled by a rheostat inserted in the field circuit. When it is desired to raise the terminal voltage, resistance is cut out of the field circuit. This causes an increase in field flux and a corresponding increase in terminal voltage.

SELF-EXCITED GENERATOR.- The external characteristic curve of a self-excited generator is shown in fig. 21. When the machine is unloaded, the terminal voltage equals the generated e m f. As more and more current is delivered, the terminal voltage drops farther and farther from the no-load value. In this respect the self-excited generator behaves like a separately excited generator except that the rate at which the terminal voltage decreases is greater in the former than it is in the latter. This is due to the fact that there is another factor which is effective in lowering the voltage as the load increases. Figs. 20 and 21 show that in both generators the terminal voltage drops as the armature current increases, because of armature reaction and IR drop. In the self-excited generator there is a third factor--the drop in voltage due to the first two factors causes a decrease in the field current, and as a result less flux is produced. Therefore, less voltage is generated (see curve 'c').

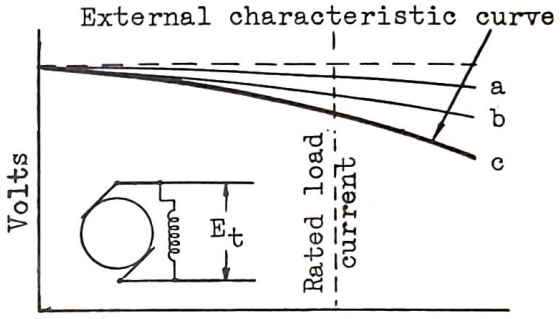


Fig. 21 Characteristic curves of the self-excited generator

It may appear that the generated e m f in a self-excited generator will drop to zero or nearly so as soon as the load is applied, because the three factors causing the voltage drop are cumulative (that is, a lesser terminal voltage establishes a weaker field, and a weaker field generates a lesser e m f, which still further weakens the field, etc.). If the iron were not saturated to a certain extent, this cumulative action would reduce the terminal voltage to nearly zero. For instance, if a terminal voltage drop of 10% reduced the flux 10%, the generator would be unable to carry a load. A voltage drop of 10% does produce a 10% drop in the field current, but this produces only a 1% or 2% drop in the field flux, as can be seen in fig. 19b. This small decrease in field flux will cause a very small decrease in voltage, etc. It should be apparent from this discussion, then, that a self-excited generator operated at a high flux density will maintain a more constant voltage than one operated at a low flux density.

BUILDING UP OF A SELF-EXCITED GENERATOR.- If the resistance of the field circuit in a generator is kept constant, the current flowing through it is directly proportional to the terminal voltage. If a curve is plotted showing how the field current varies with the terminal voltage, a straight line will result. For example, if the resistance of the field circuit is 5 ohms, 2 amperes will flow at 10 volts, 4 amperes at 20 volts, 6 amperes at 30 volts, etc. This relation is shown by line 'a' in fig. 22. Line 'b' indicates the voltage-current relation when the resistance of the field circuit is 12.2 ohms, and line 'c' indicates the relation when the resistance of the field circuit is 20 ohms. If should be noted that the higher the resistance of the field circuit, the greater the slope of the resistance curve.

Fig. 23 shows the saturation curve of the field drawn on the same graph and to the same scale as the resistance curve. In this particular case the resistance of the field circuit is 12.2 ohms. The voltage of the generator is built up as follows: The small amount of residual magnetism in the field is cut by the armature conductors, and a voltage of 6 volts is generated at the brushes. Since the field circuit is connected directly across the brushes, .6 of an ampere is sent through the field.

But this field current (referring to the magnetization curve) causes 14 volts to be generated. This voltage (referring to the resistance curve) sends 1.1 amperes through the field circuit. As a result, 24 volts are generated, and so on. It may be seen from the curves that each value of field current produces a voltage in excess of its previous value, and this higher voltage in turn increases the field current (that is, the action is cumulative). The machine will continue to build up in this way until the 110 volt point is reached. At this point the field resistance curve crosses the saturation curve.

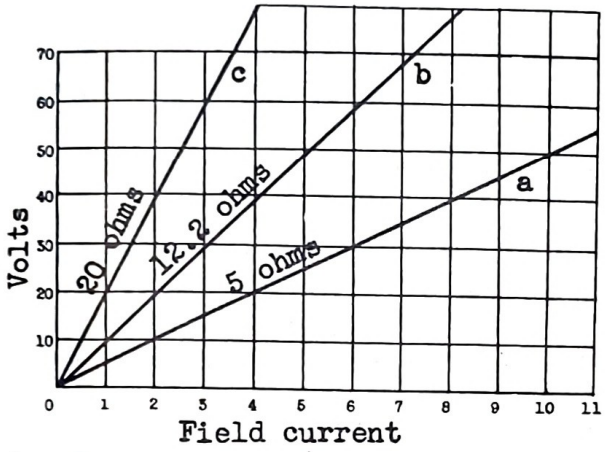


Fig. 22 Voltage-current relations of fields with different resistances

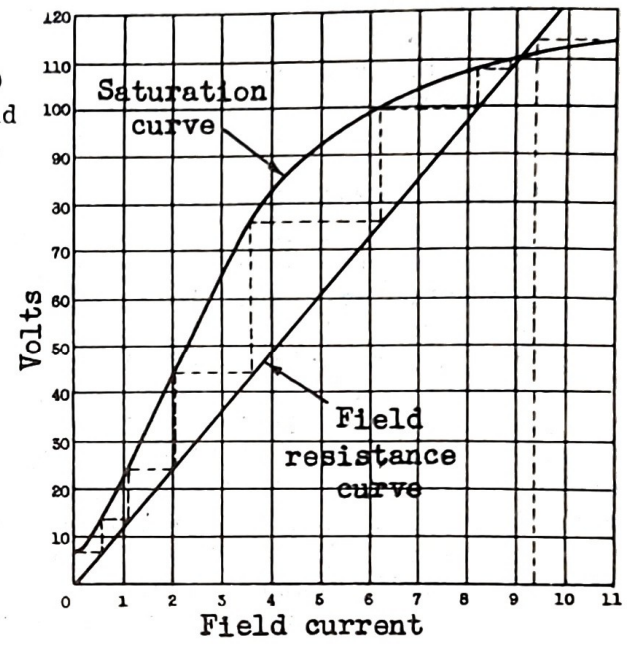


Fig. 23 Building up of a shunt generator

The following illustration will show why the voltage will not rise higher than 110 volts. Assume that somehow 113 volts were generated. This voltage would produce a field current of only 9.3 amperes, and with this field current, only 111 volts would be generated. This voltage in turn would set up a smaller current, resulting in a smaller generated voltage. This procedure would continue until the terminal voltage would become 110 volts.

SERIES GENERATOR.- The saturation curve of a series generator (curve 'a', fig. 24) does not differ from that of a shunt machine. The external characteristic curve (curve 'c') is similar in shape to the saturation curve, but lies below it, for the following two reasons. First, the flux per pole is reduced, due to armature reaction, which causes a reduction in the voltage, as indicated by curve 'b'. Second, the resistance of the armature winding, field winding, and brushes causes an IR drop, which is indicated by the external characteristic curve 'c'.

In the past, series generators were extensively used for series arc lighting. Even though arc lamps have been replaced to a great extent by series tungsten lamps, series generators are still used to supply power to these systems.

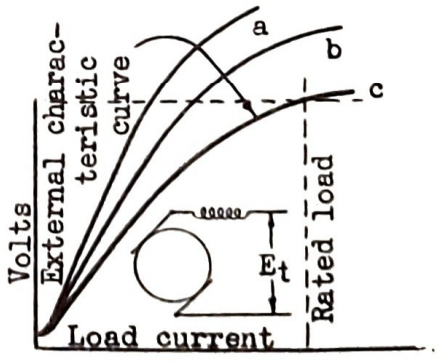


Fig. 24 External characteristics of a series generator

For proper operation, arc lamps and series tungsten lamps require a constant current. For this reason some kind of regulator must be connected to the line to prevent current fluctuation. A very simple type of regulator for this purpose is a carbon pile rheostat operated by a solenoid as shown in fig. 25.

When the current in the external circuit increases, the pull on the solenoid also increases and the carbon pile is compressed. This has the effect of reducing the resistance of the rheostat so that more current is shunted from the series field coils. The flux in the magnetic circuit is therefore reduced, and the current drops until the line current reaches the value for which the pull of the solenoid is adjusted.

As series generators are usually connected in a circuit that demands a constant current, they are sometimes called constant-current generators. It should be understood, however, that these machines are so-called not because they tend to maintain a constant current but because they are used in a circuit whose current must be kept constant, an external regulating device being used to keep it constant.

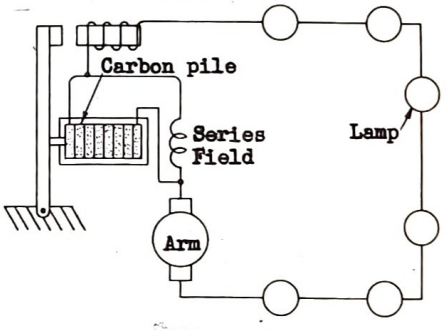


Fig. 25
Automatic regulator for a constant-current generator

COMPOUND GENERATOR.- In practice, power circuits require a constant voltage, especially lighting circuits. If a shunt generator, or even a separately excited generator, were used to supply power to these circuits, large variations in load would produce large voltage variations unless the field current was adjusted by a rheostat as the load changed. By using a compound generator, the desired voltage regulation may be automatically obtained without adjustment of the field rheostat. The curves in fig. 26 show some of the external characteristics that may be obtained from compound generators. The series winding in compound generators is usually connected to aid the magnetizing action of the shunt winding. A machine so-connected is said to be cumulatively-compounded. Its external characteristics depend upon the ampere-turns in the series field. By properly adjusting these ampere-turns the increase in terminal voltage due to the series field may be made to compensate for the drop in voltage due to the increased armature reaction and armature IR drop. In this case the series field also maintains a practically constant terminal voltage of the shunt field and the field current will not drop as the load increases. It is apparent that the three causes for voltage drop in a shunt generator are completely eliminated by the series field. The external characteristic of such a generator is shown by curve 'a' in fig. 26. In this case the effect of the series field is to cause the generator to deliver the same terminal voltage at both no load and full load, and for this reason the machine is said to be flat-compounded. Actually, however, curve 'a' is not exactly flat, because it is not possible to maintain a constant terminal voltage for all values of armature current below full load. The nearest approach is tc adjust the series field ampere-turns so that the terminal voltage will rise slightly and then drop again, reaching the same voltage at full load as at no load. When the series ampere-turns are adjusted so that the terminal voltage of the generator is greater at full load than at no load, the machine is said to be over-compounded (see curve 'b', fig. 26). When the terminal voltage is less at full load than at no load, the machine is said to be under-compounded. Except those supplying power for welding, generators are seldom under-compounded. They are usually designed to be considerably over-compounded, and the degree of compounding is then regulated by shunting more or less current from the series field by means of a resistance called a shunt (fig. 26). For small machines the shunt is usually made of German silver ribbon, and for large ones it is usually made of cast iron grids.

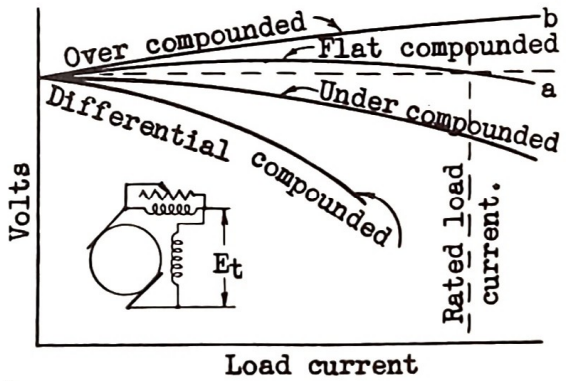


Fig. 26
Compound generator characteristics

The resistance is ordinarily adjusted at the factory when the machine is tested and need not be changed unless it is desired to change the operating characteristics.

If the terminal voltage at a generator remains constant, the voltage at a distant distribution point will decrease as the load is applied, because of the increased IR drop in the line wires. This will be made clear by considering fig. 27, which shows a generator at A supplying power to a group of lamps at B. If the voltage at A remains constant as the load increases, the voltage at B will fall, because this voltage is always equal to the voltage at A minus the IR drop in the line AB. If the series field ampere-turns are adjusted so that the voltage at A is increased just enough to equal the IR drop in the line AB, the voltage at B will remain constant.

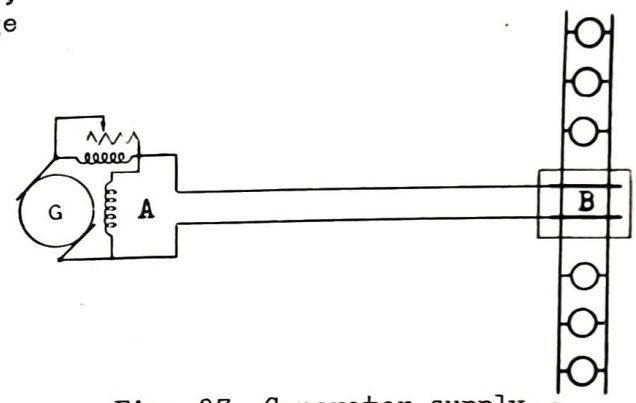


Fig. 27 Generator supplying power to distant loads

The amount of over-compounding used in practice depends upon the service for which the machine is intended. For generators near the point of power consumption, the degree of over-compounding may be as low as 3%, while for generators supplying power to a railway it may be as high as 10%.

FACTORS AFFECTING THE BUILDING UP OF A SELF-EXCITED GENERATOR.- The e m f of a generator may fail to build up for one or more reasons. Chiefly among these reasons are: (a) the field circuit may be reversed, (b) the resistance of the field in a shunt generator or the resistance of the external load in a series generator may be too high, (c) the speed may be too low, (d) there may be insufficient residual magnetism.

The field must be connected to the armature so as to cause the field current to pass through the winding in a direction that will increase the flux, that is, produce the building up action referred to in lesson 34. If on the first trial the field connection is found to be wrong, the error may be remedied by reversing the field connection to the armature, or by reversing the direction of armature rotation if this is permissible. This latter case reverses the polarity of the generator, causing current to flow in the opposite direction through the external circuit.

Too high a resistance in the field circuit may be caused by neglecting to cut resistance out of the field rheostat, by poor connections in some part of the field circuit, or by poor contact between brushes and commutator due to grease or dirt. Due to these conditions the machine may completely fail to build up or may build up to a low value.

The starting of the building up of a generator depends upon speed as well as residual magnetism. A reduction in either of these may cause the machine to not generate a voltage. Occasionally it is necessary to over-speed a generator in order to start it to building up, after which it may be brought down to normal speed. This action compensates for a subnormal residual magnetism.

It is usually necessary to maintain a fixed polarity at the generator. If a generator builds up in reverse, which sometimes happens after a shut down, it becomes necessary to change the polarity back to the original condition. To do this, the residual magnetism must be reversed. This may be accomplished by sending a current through the field coils from an external source, so as to reestablish the residual magnetism in the proper direction. Occasionally in substations, a compound generator that is to be paralleled with others builds up with its polarity reversed. In this case the residual magnetism is reestablished in the proper direction merely by energizing the series field.

In power plants, power is usually supplied from several smaller units instead of from one large generator, for the three following reasons. (1) The efficiency of the power station may be maintained at a high point by varying the number of generators in service, so that the machines in use operate at approximately full load. (2) A generator that breaks down may be removed from the circuit for repairs without interrupting the power supply. (3) Generators may be added to the system as the power demand grows.

SHUNT GENERATORS IN PARALLEL.- The generators in power stations are connected in parallel through a common bus line, to which the feeders are also connected. This is shown in fig. 28a. The division of the load may be regulated easily in shunt generators, because of the drooping characteristics. The load may be shifted from one generator to another merely by manipulating a field rheostat.

Fig. 28b shows the characteristics of two shunt generators, A and B, which have their rheostats adjusted so that they supply the same e m f (130 volts) at no load. Generator B has a more drooping characteristic than generator A. If a load is connected to the bus line, causing A to deliver 60 amperes, B will deliver 40 amperes and the bus voltage will be 120 volts. If the load is increased so that A carries 80 amperes, B will carry 55 amperes and the e m f will be 115 volts.

Suppose it is desired to have each machine carry 50 amperes. This result is obtained by decreasing the field excitation of generator A or increasing that of generator B. If the latter is done, the voltage characteristic of generator B will be raised, as indicated by curve B' (fig. 28). In this case the bus line e m f is 123 volts. This voltage can be raised, while keeping the currents equal, by increasing the field excitation of both generators. For generators of unequal capacities, the loads are generally divided in proportion to their ratings.

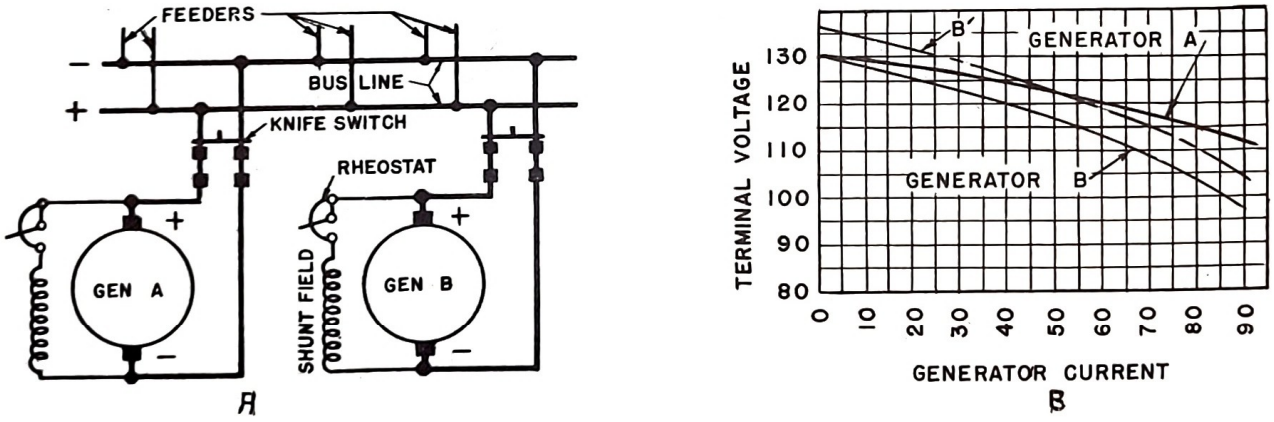


Fig. 28 Characteristics of two shunt generators in parallel

COMPOUND GENERATORS IN PARALLEL.- Undercompound generators also operate satisfactorily in parallel, but overcompounded generators will not operate satisfactorily in parallel unless their series fields are paralleled. This is accomplished by connecting the two negative brushes together, as shown in fig. 29a. The conductor used to connect these brushes is generally called an equalizer.

Suppose that an attempt is made to operate the two generators in fig. 29a in parallel without an equalizer (the external characteristics of the two machines are assumed to be as shown in fig. 29b). When generator A supplies 20 amperes, B supplies 60 amperes, and the total load is 80 amperes at 120 volts. If, for any reason, the current supplied by A increases slightly, say to 30 amperes, the current in the series field will increase and raise the generated e m f to 122 volts.

Since the total current is 80 amperes, the current of generator B must drop to 50 amperes, and as a result, its series field is weakened. This causes machine B to generate 119 volts. The result is that the load on generator A increases and that on generator B decreases. This will continue until in a very short time generator A will be driving B as a motor, in which case the current in the two machines will be in the direction shown in fig. 29-1. After machine B changes from a generator to a motor, the current in the shunt field will remain in the same direction, but the current in the armature and series field will reverse. Thus the magnetizing action of the series field opposes that of the shunt field. As the current taken by generator B increases, the demagnetizing action of the series field becomes greater and the resultant field becomes weaker. The resultant field will finally become zero, and at that time machine B will short circuit machine A, opening the breaker of either or both machines.

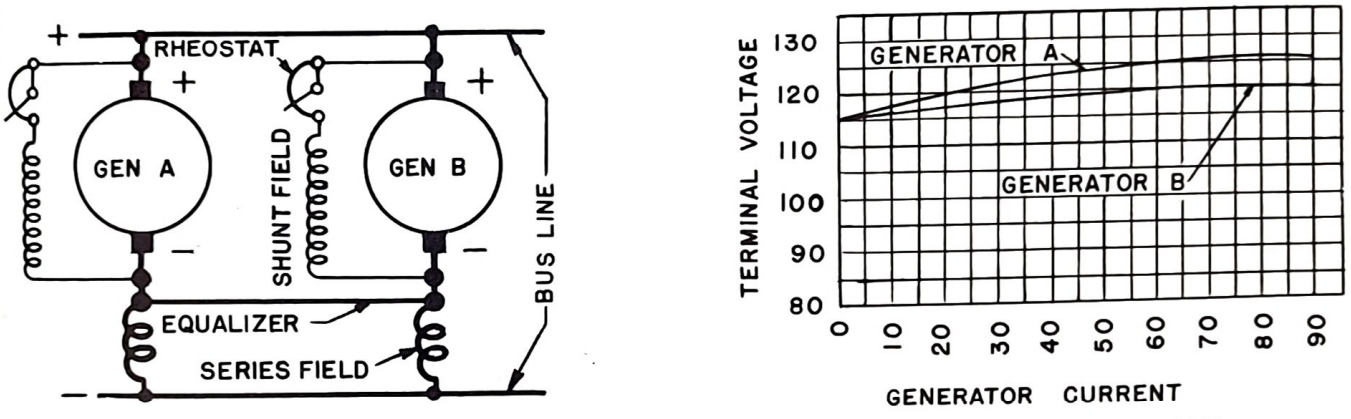


Fig. 29 Characteristics of two compound generators in parallel

When the equalizer is used, a stabilizing action exists and neither machine tends to grab all the load. To consider this, suppose that the current delivered by generator A increases (fig. 29a). This increased current will not only pass through the series field of generator A, but also through the equalizer and series field of generator B. The voltage of both machines therefore increases, and generator B will take part of the load.

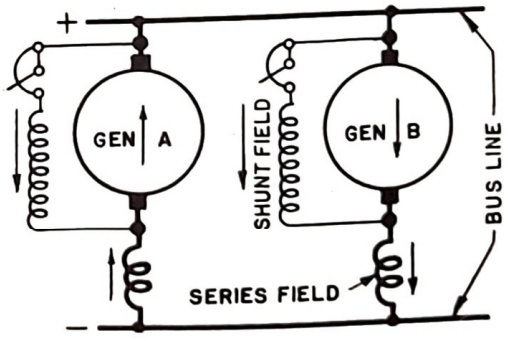


Fig. 29-1
Direction of current through a machine that is motorized

It was stated that the load on two shunt generators may be divided as desired merely by manipulating the field rheostats. It is usually desirable to have this division remain approximately constant at all loads. In compound machines of equal capacities, this takes place only if they have similar external characteristics and equal series field resistances. In machines of unequal capacities, the external characteristics must be similar, but the series field resistances must be inversely proportional to the capacities of the machines. If the latter condition does not exist, sufficient resistance should be connected in series with the proper series fields to bring about the desired condition.

Compound generator characteristics cannot be adjusted by means of series field diverters so that the loads on the machines divide as desired. In fig. 29a, suppose that the series field of generator A is shunted by a diverter. This diverter will also shunt the series field of generator B, since the bus line and equalizer have negligible resistance. In this case the diverter lowers the external voltage characteristics of the machine, but does not affect the load division.

CONNECTING A GENERATOR TO A BUS LINE.- Suppose it is desired to connect generator B of fig. 29-2 to a bus line. The generator is first brought up to its rated voltage and the negative and equalizer switches are then closed, causing some of the load current to pass through the series field of machine B. The voltage of generator B is then adjusted to equal that of the bus line, and the positive switch is closed. This machine is then loaded by increasing its field strength.

To shut down a generator, its load is reduced to zero by weakening the shunt field, the positive switch is opened, and then the other two switches are opened.

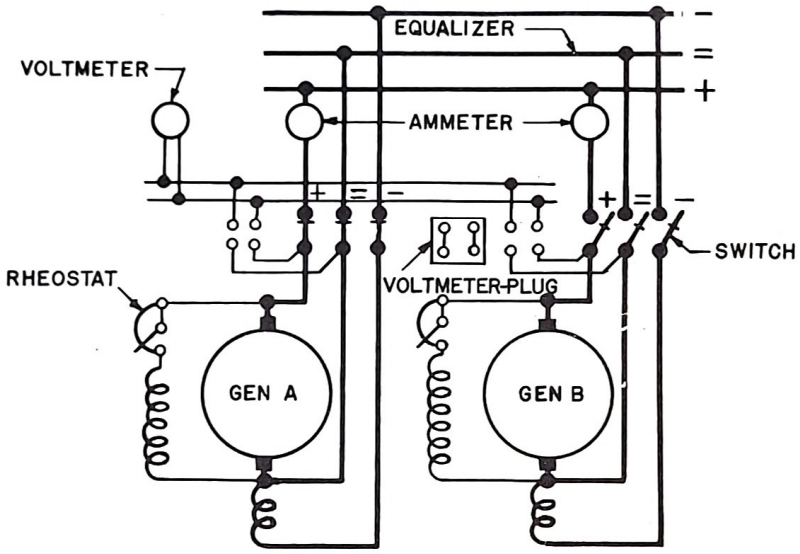


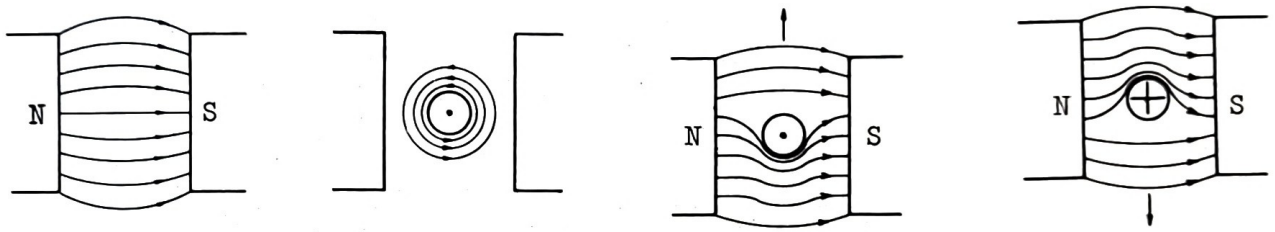
Fig. 29-2 Wiring diagram of two generators to be paralleled

HOME WORK

1. With an increase in load, (a) why does the voltage of a shunt generator drop? (b) Why does the voltage of a series generator increase?
2. What conditions prevent a shunt generator from building up?
3. How are the external characteristics of compound generators changed?
4. Give at least one industrial application of generators with external characteristics as follows: (a) flat compound, (b) over compound, (c) differential compound.
5. A 50 kw generator supplies power to a load A feet away. If the power is transmitted through a 0000 cable, what is the terminal voltage of the generator at no load and at full load in order to maintain 230 volts at the load?
6. A 250 volt, B kw, compound generator has a .5 ohm armature, a .3 ohm series field, and a 200 ohm shunt field connected long shunt. (a) Determine the current in the armature, shunt field, and series field at full load. (b) Determine the generated e m f at full load.
7. To obtain the same voltage at no load as at full load, the field current of a 120 volt, 4 kw, shunt generator must be changed from 1.5 to 2 amperes. The shunt field has 300 turns per pole. If this machine is to be equipped with a series field to give flat compound characteristics, how many turns will be required in this field?
8. (a) Give the procedure for connecting a generator with an equalizer to a bus line. (b) Give the procedure for disconnecting this generator from the bus line.
9. Two generators of 100 and D kw capacities are connected in parallel. If the series field resistance of the 100 kw generator is .0015 ohm, what must be the series field resistance of the other to properly divide the load?

A generator is a machine for converting mechanical energy into electrical energy. The electric motor, on the other hand, converts electrical energy into mechanical energy. The structure of a D.C. generator is essentially the same as that of a D.C. motor. They usually differ slightly in detail of design because of different operating conditions. For example, the generators are usually of the open type; that is, the armature and field windings are exposed; whereas, motor must often be partially or entirely enclosed to protect the winding from injury. However, the same machine may be run either as a generator or as a motor.

PRINCIPLE OF THE MOTOR - Fig. 30a shows a uniform field between the opposite poles of two magnets. In fig. 30b is represented the cross-section of a conductor placed between the two poles and carrying current toward the observer. Let us assume that the field due to the north and south poles has been temporarily removed. By applying the thumb rule (see lesson 17) we find that the lines of force around the conductor are in a counter clockwise direction.



(a) (b) (c) (d)

Fig. 30 Force acting on a current carrying conductor in a magnetic field.

Further, let us suppose that the conductor of fig.30b is placed in the magnetic field of fig. 30a; the resultant magnetic field would then be as shown in fig. 30c. Above the conductor the lines of force are weakened because the two fields are opposite in direction and tend to destroy each other. Below the conductor the lines of force are strengthened because they are in the same direction. Magnetic lines, like rubber bands under tension, tend to straighten out, and, as a result, the conductor in fig. 30c is forced upward. If the current in the conductor is reversed as shown in fig. 30d, the direction of motion will be reversed, because in this case the lines above the conductor are strengthened, while those below are weakened.

The operation of an electric motor thus depends upon the principle that a conductor carrying current in a magnetic field tends to move at right angles to the field.

FLEMING'S LEFT HAND RULE - There is a definite relation between the direction of the lines in a magnetic field, the direction in which the conductor tends to move. This relation is expressed by Fleming's left hand rule. This rule is applied in the same way as the right hand rule, except that the left hand is used The rule is illustrated in fig. 31 and may be stated as follows:

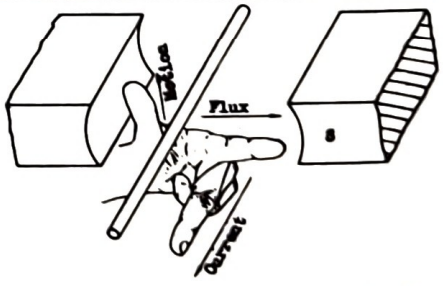


Fig. 31 Fleming's left hand rule.

Extend the thumb, the fore finger, and the middle finger at right angles to one another. Now turn the hand in such a position that the first finger points in the direction of the lines of force and the second finger in the direction of the current in the conductor; then the thumb will point in the direction of motion of the conductor.

FORCE EXERTED ON A CONDUCTOR - The force acting on a conductor carrying current while in a magnetic field is directly proportional to the field strength, the active length of the conductor, and the current flowing through it.

The force produced may be computed by the equation

$$F = \frac{8.85\ BI\ell}{10^8} \qquad (8)$$

where F = force in pounds, B = flux density in lines per square inch, ℓ = active length of the conductor in inches, and I = current in amperes.

EXAMPLE - Suppose that the conductor in fig. 31 is 12 inches long and is carrying a current of 50 amperes, and that the flux density is 70,000 lines per sq. inch. What upward force acts on the conductor?

The force on the conductor, $F = \frac{8.85 \times 70{,}000 \times 50 \times 12}{10^8} = 3.6$ lbs.

TORQUE OF A MOTOR - Since the armature of a motor is the same as that of a generator, the current from the supply line must divide and pass through the several paths of the armature. The currents through the conductors under a pole will all be in the same direction as shown in figs. 32a and 32b. In the bipolar machine of fig. 32a, the current flows toward the observer under the north pole and away from the observer under the south pole. The forces produced by the current in the conductors are therefore, all additive, as indicated by the arrows.

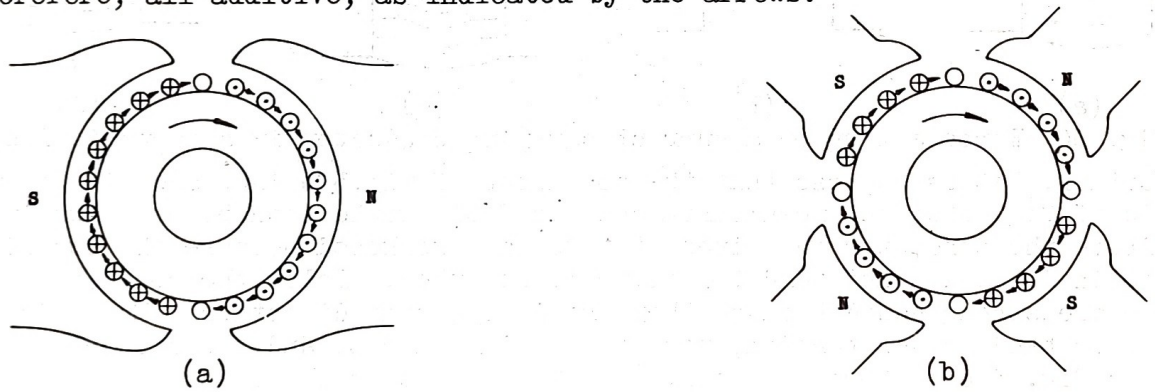


Fig. 32 Development of torque in an armature.

When a conductor moves from one side of a brush to the other, the current in that conductor is reversed, and, since it then comes under the influence of the next pole, which is of opposite polarity, the direction of the force remains the same. In a four pole machine (fig. 32b) the current flows in opposite directions under poles of unlike polarity so that the total force due to the current is the sum of the forces produced by the individual conductors.

The effect of these added forces in rotating the armature does not depend upon their magnitude (pounds pull) alone, but also upon the arm, that is, the radial distance at which they act. This effect is usually expressed as a product of the force and the length of the arm and is called torque. Expressed by an equation

$$T = Fr \qquad (9)$$

where T = torque expressed in pound feet, F = force in pounds, and r = radius in feet about which the added forces act.

EXAMPLE - In fig. 32a assume that the 20 active conductors are 10 inches long and 3 inches from the center of the armature. If the current through each conductor is 20 amperes and the air-gap flux density is 60,000 lines per square inch, find the torque developed.

The force on each conductor, $F = \frac{8.85 \times 60{,}000 \times 20 \times 10}{10^8} = 1.062$ lbs.

The total force produced by 20 conductors = 1.062 × 20 = 21.24 lbs. Then the torque produced is T = 21.24 × 5/12 = 5.31 lb-ft.

POWER REQUIRED TO DRIVE A GENERATOR.- Whenever the armature of a generator is delivering current, a motor effect which opposes the motion is set up. This is readily explained by reference to fig. 33. Assume that 'ab' represents a conductor on the surface of the armature. When 'ab' is at rest, there is no force acting on the conductor. Just as soon as 'ab' is moved downward, however, a current will flow in the direction 'a to b'. The lines of force around the conductor, due to the current, will have a clockwise direction; hence, the lines above 'ab' will be weakened and those below will be strengthened. This will produce an upward force that will oppose the driving action.

If the current in 'ab' becomes greater, the motor effect will be increased, since the flux around 'ab' will be increased. If 'ab' is not connected to a load, there will be no opposing force, because there will be no magnetic field produced by the current through the conductor.

Thus little power is required to rotate a generator when the armature is delivering no current, but as the armature current increases, the strength of the field surrounding each conductor will increase in the same proportion. Hence the greater the amount of current delivered by a generator the greater the amount of driving power required. This is strictly in accordance with the law of conservation of energy, which may be stated as follows:

<u>The energy output of a machine can never be greater than the energy input.</u>

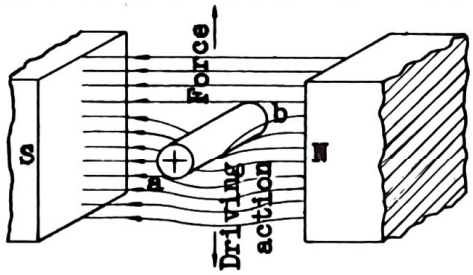


Fig. 33 Motor action produced in a generator

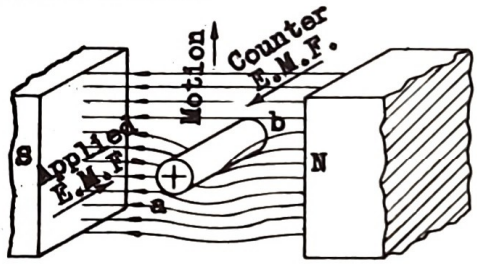


Fig. 34 Direction of voltages in an armature conductor

COUNTER ELECTROMOTIVE FORCE.- We have just considered the motor effect in a generator. Likewise we shall see that every motor is subject to a generator effect.

Suppose that 230 volts are supplied to a 5 H P, 850 r p m motor. The armature resistance of this size motor is about .1 ohm. According to Ohm's law, the armature current will be 230 ÷ .1 or 2300 amperes. Of course such a high current would burn out the armature winding; then we suspect that something besides the armature resistance keeps the current at a reasonable value. We will now determine what this restraining action is.

Consider that a voltage is applied in the direction shown in fig. 34. A current will flow in the same direction, or from 'a to b', and according to Fleming's left-hand rule the conductor will be forced upward. On moving upward the conductor will cut lines of force, and according to Fleming's right-hand rule, an e m f will be induced in the opposite direction to the impressed e m f, or from 'b to a'. This counter voltage always opposes the impressed voltage, and is called the counter (or back) voltage. It is directly proportional to the armature speed and field strength. The effective voltage across the armature equals the applied voltage E_a minus the counter voltage E_g. If an armature has R ohms resistance, the current flowing through it can be determined by the equation

$$I = \frac{E_a - E_g}{R} \qquad (10)$$

Suppose that the 5 H P motor considered previously has a counter-e m f of 228 volts at full load. Then the full load current is

$$I = \frac{230 - 228}{.1} = 20 \text{ amperes}$$

TORQUE AND POWER.- Solving for E_a in equation 10,

$$E_a = E_g + IR$$

and multiplying both members of the equation by I, we have

$$E_aI = E_gI + I^2R \qquad (11)$$

The term E_aI represents the power supplied to the armature, and I^2R is the power lost as heat due to the ohmic resistance of the armature. The remainder of the power, E_gI, must therefore be the amount of mechanical power developed by the armature. Not all of this developed power is available at the shaft or pulley, for some of it is lost in overcoming friction of the bearings and brushes, windage resistance, hysteresis and eddy current in the armature core and pole faces. All these losses produce a mechanical drag on the armature. The remainder of the power, after subtracting these losses, appears as power available at the pulley or shaft for driving the external load. Nevertheless, in practice it is sufficiently accurate to assume that the power supplied by the pulley is E_gI watts.

Then the horsepower developed by the armature is

$$H\ P = \frac{E_gI}{746} \qquad (12)$$

But equation 11 (lesson 10) shows that the horsepower may also be expressed as

$$H\ P = \frac{TN}{5252} \qquad (13)$$

Then it follows that the right-hand members of equations 12 and 13 are equal, that is

$$\frac{E_gI}{746} = \frac{TN}{5252}$$

Solving for T,
$$T = \frac{5252}{746} \times \frac{E_g}{N} \times I \qquad (14)$$

But when studying generators, we learned that

$$E_g = \frac{P\Phi ZN}{60b10^8}$$

Then
$$T = \frac{5252}{746} \times \frac{P\Phi ZN}{60b10^8N} \times I \qquad (15)$$

or
$$T = \left(\frac{PZ}{8.5b10^8}\right)\Phi I$$

For a given motor the expression within the parenthesis is constant. Then this equation may be written

$$T = K_1 \Phi I \qquad (17)$$

where K_1 is a constant.

Example.- A simplex lap wound armature of a 4 pole motor has 140 active conductors, and there are 6×10^6 magnetic lines per pole. If at full load the motor runs 1200 r p m and takes 6 amperes, determine (a) the torque produced, and (b) the horsepower developed.

(a) Substituting in equation 16, we have

$$T = \left(\frac{4 \times 140}{8.5 \times 10^8 \times 4}\right) 6 \times 10^6 \times 6 = 5.93 \text{ pound-feet}$$

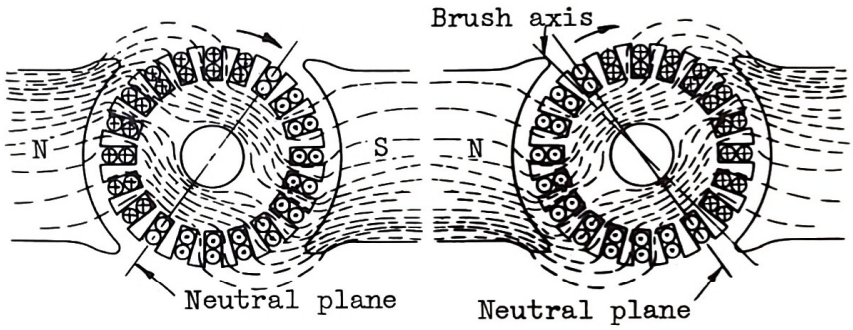
(b) Using equation 13 to find the horsepower,

$$H P = \frac{5.93 \times 1200}{5252} = 1.35 \text{ horsepower}$$

HOME WORK

1. What factors govern the strength of the counter-electromotive force?
2. What relation exists between the speed of a motor and the armature current?
3. Why does a motor take a very large current when starting?
4. What is the net voltage acting on an armature circuit?
5. Assume the wire in fig. 31 to be 8 inches long and to lie entirely within the magnetic field. The current carried by the conductor is 40 amperes, and the flux density is 60,000 lines per square inch. Find the upward force exerted on the conductor.
6. The current taken by an armature is 10 amperes, and its resistance is .2 ohm. If 120 volts are supplied, find the counter-e m f.
7. Find the horsepower developed by the motor in problem 6.
8. Determine the power in watts supplied to the motor in problem 6.
9. The armature of a 4 pole motor contains 48 coils of 6 turns each. The flux per pole is 2×10^6 magnetic lines. If the armature is simplex lap wound and the current taken by it is 40 amperes, what will be the torque?
10. If the motor in problem 9 is turning at 1200 r p m, what horsepower is being developed?

ARMATURE REACTION IN A MOTOR.- In a generator the armature current is in the direction of the induced e m f, whereas in a motor the armature current flows against the induced (or counter) e m f. It should therefore be expected that for the same direction of rotation and field polarity the armature flux of the motor will be in the opposite direction to that of the generator. Hence, instead of the main flux being distorted in the direction of rotation, as in the generator, it is distorted opposite the direction of rotation. The condition that exists in a generator is shown in fig. 35a, while fig. 35b shows the same machine operating as a motor. It should be observed that the direction of rotation and the polarity are unchanged, while the current is in the opposite direction. This causes the flux to likewise be distorted in the opposite direction.



(a) Generator (b) Motor

Fig. 35
Flux distribution in a generator and in a motor

As a result, in a generator the brushes must be shifted in the direction of armature rotation, whereas in a motor they must be shifted against the direction of rotation.

If it were not for the e m f of self-inductance the brush axis should be made to coincide with the neutral plane. Due, however, to the necessity of neutralizing this e m f, the brushes must be set slightly behind this neutral plane (fig. 35b). Thus in both the generator and the motor it is necessary to set the brushes beyond the neutral plane to neutralize the effect of self-inductance.

COMMUTATING POLES.- Commutating poles are just as important in motors as in generators. When a motor is not equipped with commutating poles the brushes must be shifted just as much as in a generator, if sparkless commutation is to be obtained.

Fig. 36a shows the condition that exists in a section of a multipolar machine. The corresponding flux distribution curves are shown in fig. 36b. The flux produced by the armature between the two poles is downward, and to oppose this flux, the commutating pole must be a south pole. Therefore, in a motor the commutating poles must have the same polarity as the main poles directly back of them. This is the opposite of the corresponding relation in a generator.

Direct current motors are divided into three principal types--shunt, series, and compound. They are named, as in generators, according to the way the field windings are connected.

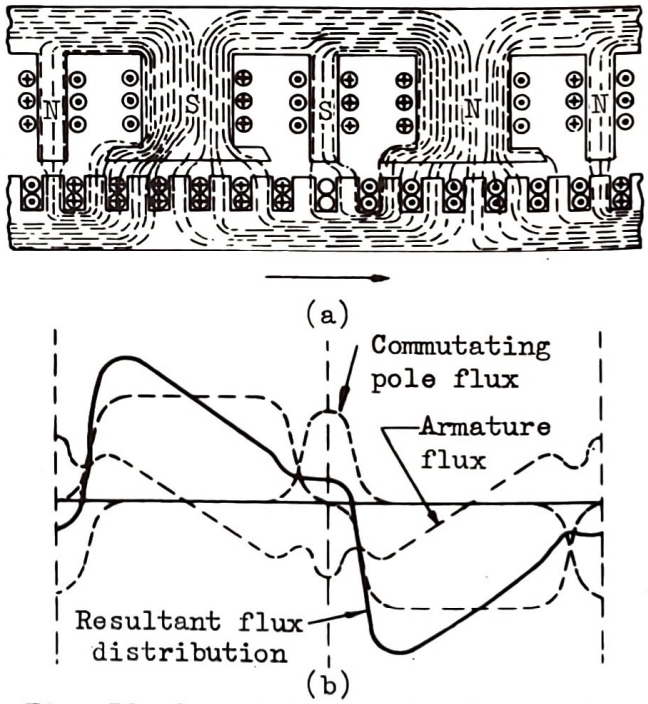


Fig. 36 Commutating poles in a motor

SHUNT MOTOR.- In a shunt motor the field is connected directly across the line; and since the line voltage is steady, the field current and field flux are constant. If such a motor is unloaded, the retarding torque is small, being due only to the winding resistance and the friction. The armature will develop a counter-e m f that will restrict the armature current to a value that will cause the motor to develop a torque equal to the resisting torque.

A motor must slow down when an external load is applied to it, because the small no-load current is just sufficient to produce a torque to overcome friction. This decrease in speed causes the generated voltage to decrease, since the field flux is constant, and more current flows through the armature (see equation 10). The armature current will continue to increase until a torque is developed to just equal that of the external load. When this point is reached, the armature current and speed will remain constant until the load is again changed. If the load is decreased, the torque developed will be greater than that of the external load. Then the speed will increase and the counter-e m f will decrease the armature current.

The foregoing discussion shows that the amount of current taken by a shunt motor is automatically regulated by the load placed upon it, which is due to the variation in speed. This is true for all types of motors--shunt, series, and compound.

The industrial application for which a motor is best suited depends on the variation of the speed and the torque with the load.

An equation suited for investigating the speed variation in a motor may be obtained by substituting for E_g in equation 10, the expression $K\Phi N$ (which is given in equation 17). This gives

$$I = \frac{E_a - K\Phi N}{R}$$

Solving for N,

$$N = \frac{E_a - IR}{K\Phi} \qquad (18)$$

. In a shunt motor, E_a, R, K, and Φ are practically constant, and I is the only variable. When the motor is carrying no load, the value of I is small because the speed and therefore the counter-e m f are both at a maximum. In equation 18, then, IR (the voltage drop in the armature) is negligible compared to E_a. At full load, IR is ordinarily about 1/20 or 5 per cent of E_a, the actual value depending upon the size and design of the machine. Consequently, at full load, the speed indicated by

$$\frac{E_a - IR}{K\Phi}$$

is about 95 per cent of the no-load value, as shown by curve A in fig. 37. This fall in speed is reduced slightly by armature reaction, which causes the flux to be less and the speed to increase correspondingly. In some cases, armature reaction is sufficient to cause the speed to remain nearly constant or even rise with an increase in load. For these reasons, a shunt motor is considered a constant speed motor, even though the speed usually decreases slightly with an increase in the load.

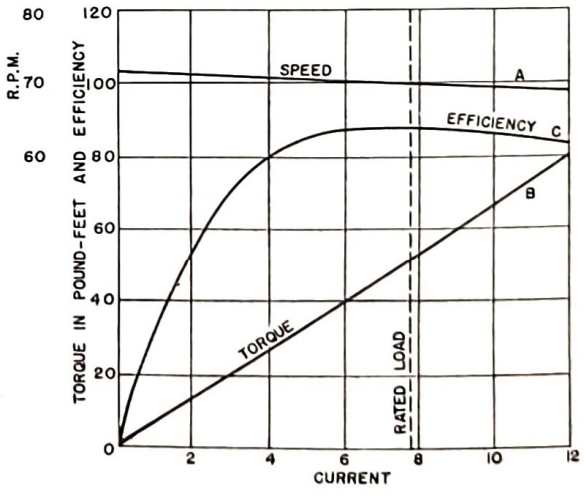


Fig. 37
Shunt motor operating characteristics

SPEED ADJUSTMENT.- The speed of a shunt motor can be changed by means of an adjustable resistance in the armature circuit or one in the field circuit (called a field rheostat). Inserting resistance in the armature circuit establishes a high power loss, and causes the speed to change considerably with a change in the load, as indicated in fig. 37-1. The most common method of changing the speed is by varying the resistance in the field circuit. Suppose that the resistance in the field circuit is increased. This causes the current through the field circuit to decrease, which in turn causes a reduction in the field flux. Thus fewer magnetic lines are cut by the armature and therefore less counter-e m f is generated. As a result, more current flows through the armature.

The increase in armature current is much greater than the decrease in field current, therefore the torque is greater and the armature increases in speed. In doing so, the counter-e m f increases and reduces the armature current. The speed increases until the developed torque becomes equal to the resisting torque, and then the motor again runs at a constant speed. Therefore, peculiar as it may seem, the speed of a shunt motor is increased by increasing the resistance of the field circuit.

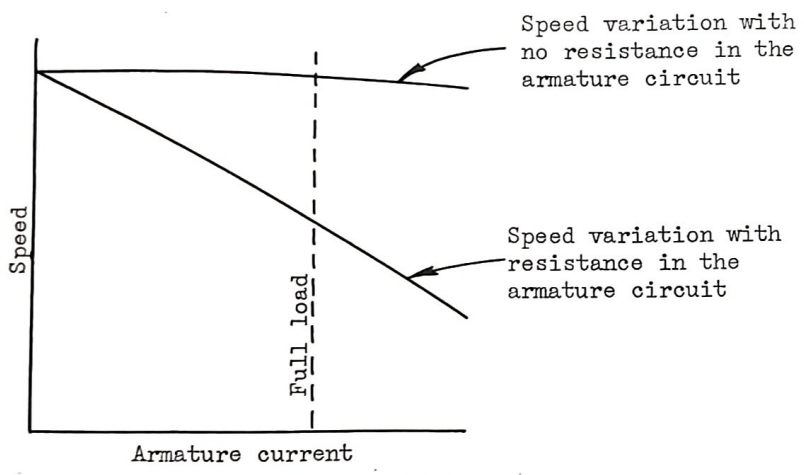

Speed variation with no resistance in the armature circuit
Speed variation with resistance in the armature circuit
Speed
Full load
Armature current

Fig. 37-1
Changing the speed by varying the resistance in the armature circuit

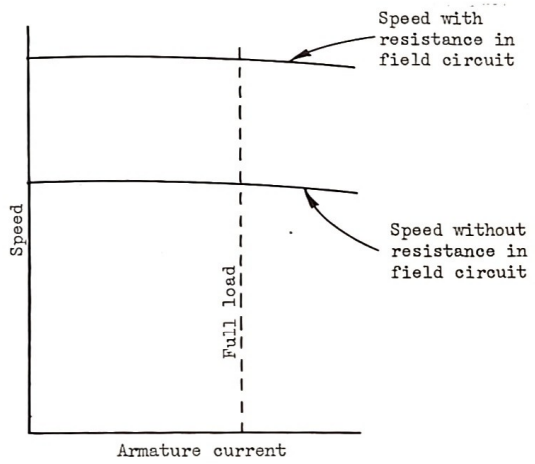


Fig. 37-2
Changing the speed by varying the resistance in the field circuit

With this method of varying the speed, a motor will run at nearly a constant speed for any setting of the rheostat (see fig. 37-2). This constant speed characteristic is desirable in many industrial applications in which the speed is adjusted at a certain value and it is important that it remain at approximately that value for load changes from no load to full load.

When a lower speed in a shunt motor is desired, some of the resistance in the field circuit is cut out. This allows more current to flow through the field. The armature conductors then cut more magnetic lines, and a higher counter-e m f is produced. This cuts down the current (and torque) in the armature, and as a result the motor runs at a lower speed.

The relation between the torque developed by a shunt motor and the current flowing through its armature winding may be analyzed easily. As stated above, the field flux is practically constant. Then, from equation 17, the torque will vary directly with the armature current. This relation is shown by curve B in fig. 37. Note that when the armature current is 6 amperes, the motor develops a torque of 40 pound-feet, and when the armature current is 12 amperes the motor develops a torque of 80 pound-feet. That is, when the current doubles the torque doubles.

Curve C shows that as the load is increased the efficiency increases rapidly at light loads, reaches a maximum at a little over half load, and decreases gradually.

This is due to the fact that at light loads the friction and copper losses are high when compared with the external load. Above full load the I^2R losses of the armature cause the efficiency to drop gradually.

The shunt motor is best suited for constant speed drives. It meets the requirements of a large range of industrial applications, such as the driving of machine tools, blowers, fans, and line shaftings.

HOME WORK

1. Name the different types of D C motors.

2. For what kind of service is a shunt motor adaptable?

3. (a) How does the speed of a shunt motor vary with the load? (b) How does the armature current vary with the torque?

4. How is the direction of rotation of a shunt motor reversed?

5. To vary the speed of a shunt motor, why is resistance inserted in the field circuit rather than in the armature circuit?

6. What will happen if the rheostat in the field circuit of a shunt motor becomes open?

7. A shunt motor connected across a 240 volt line takes 6 amperes and runs at 850 r p m. Its armature resistance is .2 ohm. At what speed will the motor run when the armature current is A amperes?

8. A 230 volt shunt motor runs at 900 r p m when taking a full load current of B amperes. The armature has a resistance of .5 ohm and the field has a resistance of 200 ohms. Find the resistance of the field rheostat required to raise the speed to 1200 r p m while the motor takes a full load current.

9. A 4 pole, 240 volt shunt motor takes C amperes at full load. The armature is simplex wave wound, has 180 active conductors, and has a resistance of .3 ohm. The flux per pole is 720,000 lines. What is the speed of the motor at full load?

10. What changes must be made in the armature winding of the motor in problem 9 so that it will run at half speed?

11. What effect will a decrease in the number of turns in the armature coils have on the speed of a motor?

12. A 4 pole shunt motor with a simplex wave wound armature runs at D r p m. At what speed will this motor run if the armature is reconnected simplex lap?

13. What will be the speed of the motor in problem 12 if the armature is reconnected duplex lap?

14. It is desired to use a 240 volt, E pole, wave wound motor on 120 volts. If the horsepower and speed are to remain unchanged, what changes must be made?

15. When developing a torque of 20 lb-ft, a 120 volt, 5 H P motor takes F amperes. What current will the motor take when developing a torque of 60 lb-ft?

SERIES MOTORS.- Equation 18 may also be applied to a series motor if R is considered to include the resistance of the series winding. Hence R, and therefore the IR drop, is slightly greater than in a shunt motor. In a series motor the flux increases almost directly with the load. Then, since the numerator in the equation

$$\frac{E_a - IR}{K\Phi}$$

decreases appreciably while the denominator increases considerably with an increase in load, it should follow that the speed decreases very much as indicated by curve A in fig. 38. As full load is approached, the field becomes somewhat saturated. Thus the field flux does not increase as much for a given increase in armature current as it does at light loads, so that near full load the speed changes less rapidly.

If the load is removed from a series motor, the speed increases rapidly, and at very light loads a motor may run at far more than safe speeds. In very small motors this is not true, since friction offers enough load to restrain a motor from running at dangerous speeds. A large series motor should always be connected to the load by gears or other positive drives, and never used with a belt drive or any other drive where it is possible for the load to be entirely removed.

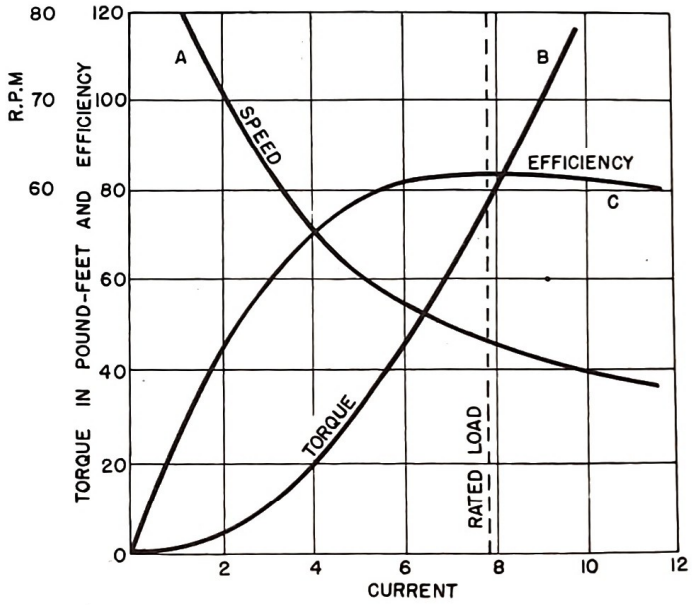


Fig. 38 Characteristics of a series motor

Equation 17 shows that the torque developed by any direct current motor varies with Φ and I. In a series motor the current through the armature also passes through the field. Then during the time the field is only moderately saturated, Φ will be almost directly proportional to I, and the torque is therefore directly proportional to I^2. This may be expressed by means of the following equation:

$$T = K_2 I^2$$

This relation is shown by curve B in fig. 38. When the armature current is 4 amperes, the motor develops a torque of 20 pound-feet, and at 8 amperes it develops a torque of 80 pound-feet. That is, when the armature current doubles the torque becomes four times as great. Thus the torque increases rapidly near and above full load. Such characteristics make the use of the series motor desirable where it is necessary to supply a large torque with a moderate increase in current. For this reason a series motor will start with a much heavier load than a shunt motor, and will accelerate with less current input.

Actually, however, saturation and armature reaction prevent the torque from increasing as rapidly as the square of the current, so that at very heavy loads the torque curve becomes almost straight.

Although the efficiency of a series motor varies about the same as that of a shunt motor (see curve C in fig. 38), the actual operating efficiency is usually considerably lower. This is due to the fact that a series motor seldom runs at its rated load, but is continually accelerating and decelerating.

Series motors are used chiefly for widely varying loads, where extreme speed changes are not objectionable, and where the operator is always present. They are used extensively for cranes and hoists, and for traction purposes. In these cases the variation of speed with the load is a favorable condition. For instance, in using a crane to lift a heavy load, it is generally desirable to proceed slowly, but in carrying a light load it is desirable to have increased speed for making rapid headway. The enormous torque of a series motor makes it very suitable for hoisting and similar work which demands frequent acceleration under heavy loads.

COMPOUND MOTORS.- As in compound generators, connections in compound motors are usually arranged so that the series winding aids the shunt winding. A motor so connected is said to be cumulatively compounded. If the series field is connected to oppose the shunt, however, the motor is said to be differentially compounded. The cumulatively compounded motor has the combined characteristics of the shunt and series motor, as may be seen in fig. 39. It has a definite no-load speed, and therefore may be run unloaded. The speed falls more rapidly than it does in shunt motors, because the field strength increases with the load. The method of speed control is the same as that used in shunt motors.

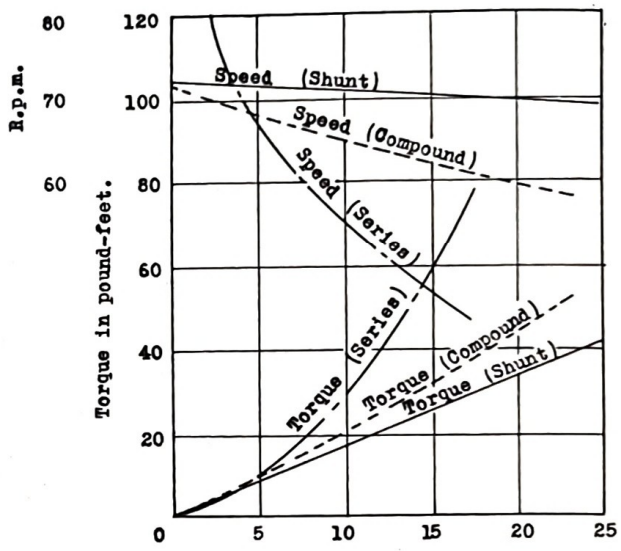


Fig. 39 Characteristic curves of shunt, series, and cumulatively compounded motors which have the same speed at light loads

The current-torque curve of a compound motor is intermediate to the curves of the shunt and series motors (fig. 39). The field strength at zero armature current is due only to the shunt winding. As the load is applied, the series turns increase the flux, causing the torque for any given current to be greater than it would be for a straight shunt motor.

The speed and torque characteristics of the cumulatively compounded motor may approach those of the shunt or series motors as limits, depending upon the strength of the two fields. If the motor contains a light series winding, it will have better torque characteristics than a shunt motor, but will largely retain the good speed regulation or efficient speed control of the shunt motor. If the motor has a light shunt winding (one sufficient to keep the no-load speed within certain limits) and a heavy series winding, it will have the characteristics of a series motor, but will not run at a dangerous speed with light loads.

To reverse the direction of rotation of any motor, the connections of the armature terminals alone, or the connections of the field winding (or field windings) alone, must be reversed. If both (or all) are reversed, the direction of rotation will remain unchanged.

Compound motors are used for driving machines that demand a fairly constant speed and are subject to irregular loads or sudden applications of heavy loads, such as presses, shears, compressors, reciprocating tools, and elevators. They are also used where it is desired to partially protect the motor by causing it to decrease in speed under heavy loads.

EFFECT OF A FLYWHEEL.- The power required by some kinds of machine tools is very irregular. In a punch press or stamping machine, for example, almost no power is required until the punch or die comes in contact with the metal to be punched or pressed. If the moving parts in such a machine are not very heavy, the current taken by the driving motor will vary widely, as shown by the solid curve in fig. 40. The motor selected to carry such a variation of current must be large enough to commutate the greatest value of current. If a comparatively over-compounded motor is used (say about 30%) with a heavy flywheel, the current through the armature will vary somewhat as indicated by the dotted curve in fig. 40. From this curve it can readily be seen that the driving motor may be much smaller when a flywheel is used (less than two-thirds as large).

The effect of a flywheel on a machine is as follows. At 'a' (fig. 40) the load on the motor and flywheel suddenly increases and causes them to slow down. As the flywheel is slowed down, it is effective in supplying energy. That is, the electrical input to the motor will not be as great as the power demanded by the load, and as the flywheel slows down it assists the motor in carrying a part of the load During this slowing down process, the current input to the motor must increase.

At 'b' the power required by the load is less than the input to the motor, so that the motor and flywheel begin to speed up and the current decreases. This procedure continues during the operation of the machine.

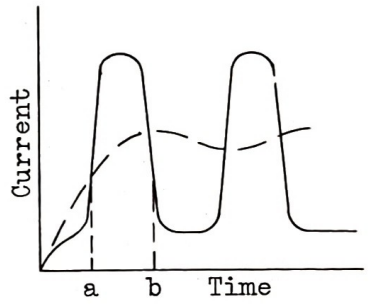


Fig. 40
Curves showing variation of current taken by motor used in driving a punch press or stamping machine

HOME WORK

1. How is the speed of a series motor affected when a load is applied? When a load is removed?

2. What precaution should be taken in using series motors?

3. How does the flux vary with the load in a series motor? How does this affect the variation of the torque with the load?

4. For what general type of loads is the series motor most suited? Why?

5. How may a shunt, a series, and a compound motor be reversed?

6. Explain the speed and torque characteristics of a cumulatively compounded motor. What advantage has this motor over the series motor?

7. The armature of a 240 volt series motor has a resistance of .5 ohm and the series field has a resistance of .1 ohm. When the machine is taking 10 amperes, its speed is 1200 r p m. Neglecting armature reaction and assuming that the flux saturation curve is a straight line, determine the speed when the motor takes 30 amperes.

8. At full load a 220 volt series motor takes 40 amperes and runs at 980 r p m. If the armature has a resistance of .2 ohm and the series field .8 ohm, compute the speed of the motor when it is connected to a 150 volt line.

9. A 220 volt, 4 H P series motor develops a torque of 12 pound-feet when the current is 10 amperes. What torque will it deliver when the current is 20 amperes?

According to lesson 36 the amount of current flowing through an armature may be determined by the equation

$$I = \frac{E_a - E_g}{R} \qquad (1)$$

where I = armature current, E_a = applied voltage, E_g = generated or counter-voltage, and R = armature resistance. R is very small in a D C motor, and at the instant of starting E_g is zero. Then if a motor is switched directly to a voltage E_a (its rated voltage), the armature current will be excessive. For instance, the armature resistance of a 5 H P, 230 volt motor is about .4 ohm. The current through the armature at the instant that the machine is connected directly to the line is 230 ÷ .4 or 575 amperes. The full load current of a motor of this size is about 20 amperes. Then the starting current is 575 ÷ 20 or 28.75 times the full load current. This high current may damage the insulation by overheating it, and the motor and attached machinery may be affected by the sudden jerk received when starting. A variable resistance is connected in series with the armature, to reduce the starting current to a limit of about 1.5 times the full load current. As soon as the armature begins to rotate, a voltage E_g is generated, which increases with the speed. Then from equation 1 it can be seen that the armature current I decreases as the motor speeds up. Thus the starting resistance may be cut out gradually. This may be accomplished in a simple and practical way by a starting resistance arranged as shown in fig. 1.

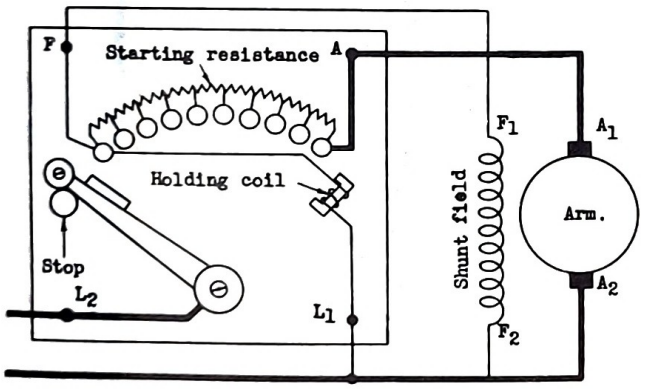


Fig. 1
Starter with no voltage release (it may be used on series, shunt, or compound motors)

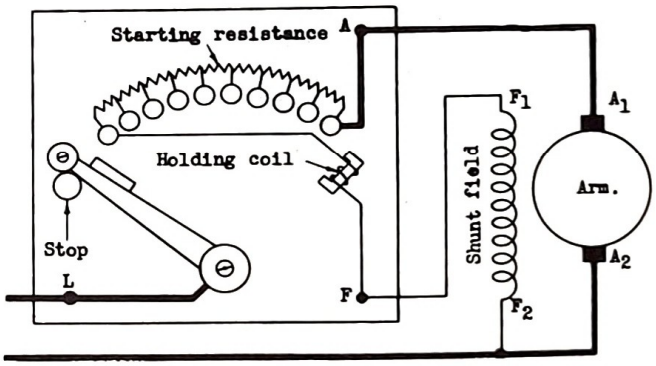


Fig. 2
Starter with no voltage release or field protection (it cannot be used to start series motors)

This starting arrangement, usually called a starter, functions as follows. When the arm is raised to the first contact, the field is connected directly across the line and the starting resistance is placed in series with the armature. The starting resistance is gradually cut out of the armature circuit as the arm is rotated slowly. When the arm moves into contact with the electromagnet, all of the resistance is cut out and the armature is connected directly across the line. The electromagnet holds the arm in a running position as long as voltage is maintained. In case of a voltage failure, the magnet releases the arm, which is pulled back to the off position by a spring. Hence the motor will not be damaged when the voltage is restored. This starter may also be used for starting series or compound motors.

The low voltage release magnet is sometimes designed to be connected in series with the shunt field (fig. 2). It has the advantage that the electromagnet releases the arm if the field circuit is opened, and the armature comes to a standstill instead of racing. This starter is used only for starting shunt or compound motors.

CONTROLLERS.- A controller is a device for regulating the operation of electrical equipment. A controller for electric motors is simply a starter which provides a convenient and safe means of performing several or all of the following functions: (a) starting and stopping, (b) accelerating and decelerating, (c) reversing, (d) regulating the speed, (e) dynamic braking or plugging.

Series motors and compound motors with a heavy series winding have industrial applications that usually demand heavy service. In some of these the motor must be frequently started, stopped, and reversed, in addition to having its speed varied continually. The stopping is usually accomplished by plugging or dynamic braking (to be explained in detail later). The need of a controller for motors rendering such rugged service has been responsible for the development of two types of controllers, a face plate type and a drum type. Each of these types is operated by a single handle.

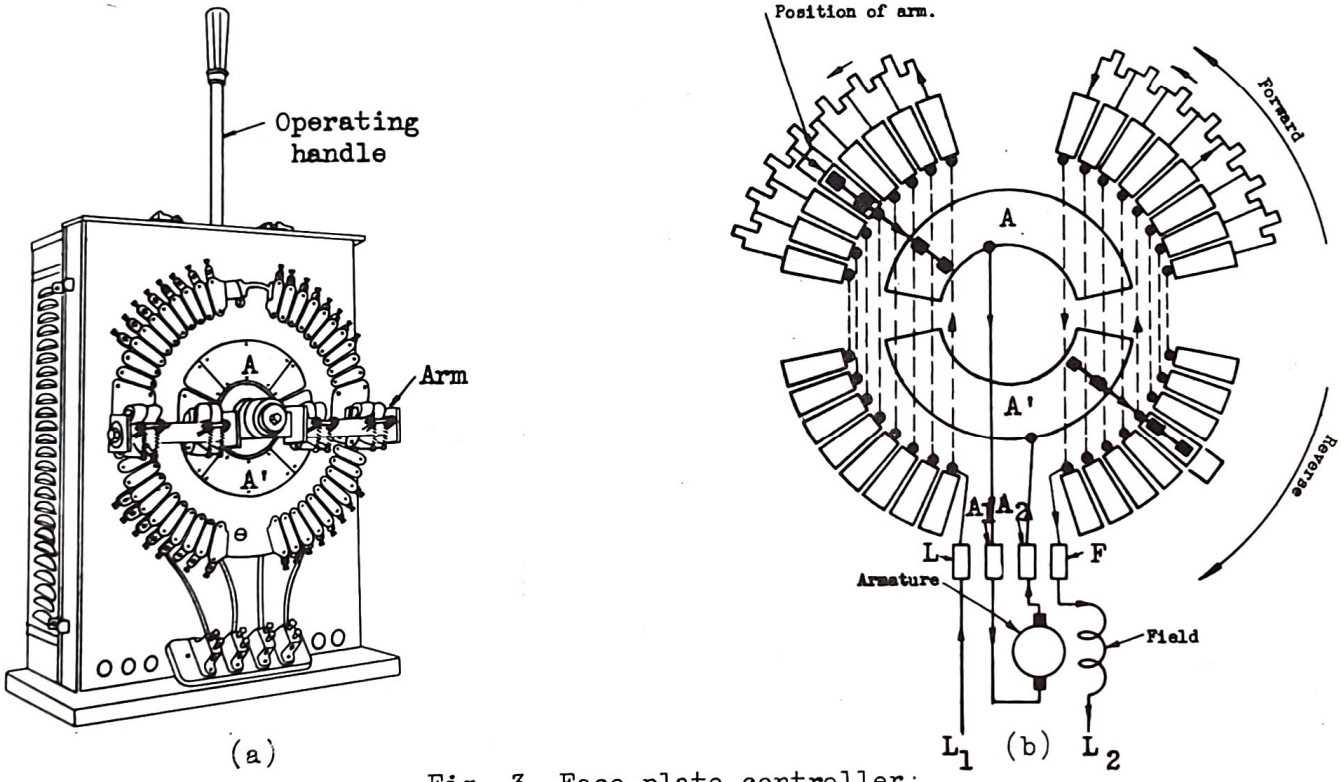


Fig. 3 Face plate controller

FACE PLATE CONTROLLER.- An E C & M face plate controller is shown in fig. 3a. Segments are mounted in a circle on the face of this controller, inside of which two arc contacts (A and A') are mounted. These contacts have renewable tips. Brushes resting on these contacts are attached to (but insulated from) the horizontal arm, which is actuated by a handle at the top of the controller. The two sets of brushes at each end of the arm are connected together (see fig. 3b), thus forming a circuit between the inner and outer contacts. The starting resistance, which is mounted at the back of the panel, is connected to the contacts as indicated in fig. 3b.

When the controller is in the "off" position, the brushes set on insulating pieces, and the operating handle is vertical.

When the handle is moved in the "forward" direction, sections of starting resistance are cut out in steps, thus causing the armature to accelerate. When the arm is in the position indicated in fig. 3b, the current flows in the direction indicated by the arrows on the wires.

When the arm is moved from the horizontal to the "reverse" direction, the current reverses in the armature, while the current in the series field remains in the same direction. This causes the motor to run in reverse.

DRUM CONTROLLERS.- One common type of drum controller is shown in fig. 4a. It consists essentially of a drum cylinder insulated from a central shaft to which an operating handle is keyed. Copper segments are attached to the drum, and are connected to or insulated from one another as the case requires. In fig. 4a the segments are connected through the drum, as indicated in fig. 4b. A series of stationary fingers is arranged to contact with the segments. These fingers are insulated from one another but connect to the starting resistance and to the motor circuit. Just under the handle a notched wheel is keyed to the shaft. A spring forces a roller into one of the notches when contacts are properly made, thus indicating to the operator the correct position of the handle.

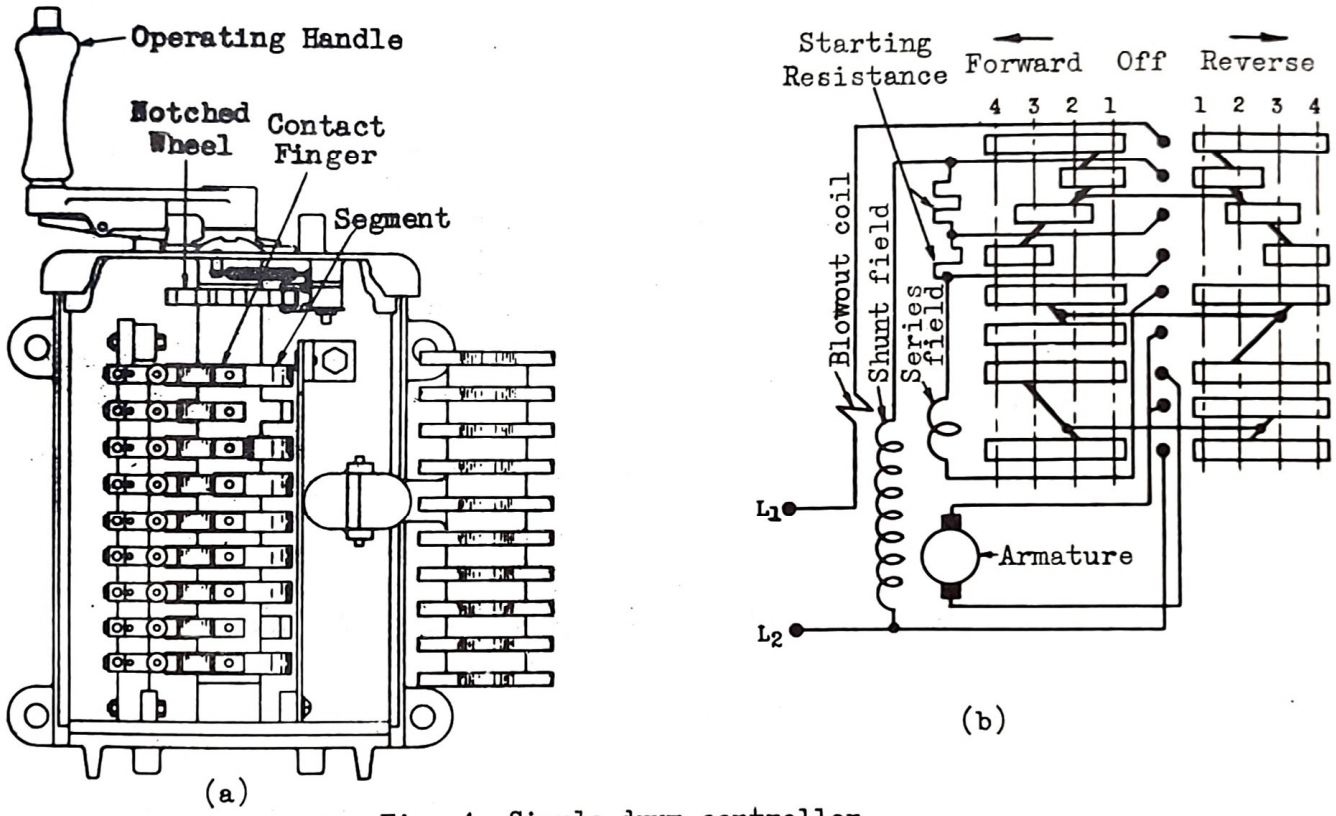


Fig. 4 Simple drum controller

In fig. 4b, when the controller handle is moved forward one notch, the fingers are at position 1. The current flows from L_1, through all of the resistance, through the series field and armature, to L_2. This starts the motor. As the handle is turned further, the resistance is cut out of the armature circuit in steps and in inserted in the field circuit. When the handle reaches notch 4, all the resistance will be in the field circuit and none in the armature circuit. This will provide maximum speed.

The current through the armature, and therefore the motor, is reversed by moving the handle in the opposite direction from the "off" position.

MAGNETIC BLOWOUT.- Since controllers are frequently operated, the fingers and corresponding contacts would soon burn if means were not provided to extinguish the electric arc formed as the contacts open.

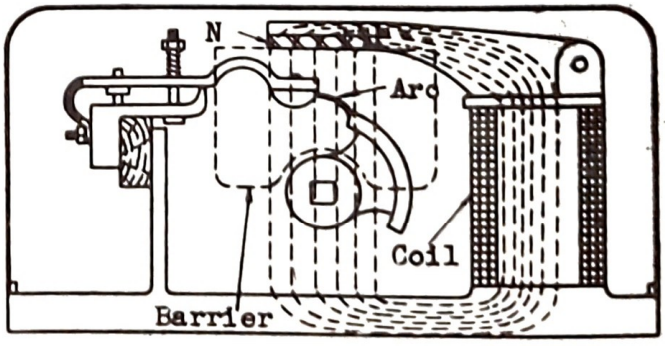


Fig. 5 Action of a magnetic blowout

This extinguishing effect is accomplished by means of a magnetic blowout, a diagram of which is shown in fig. 5. The plate N, which is over the fingers and hinged to the core of the blowout coil, extends the full length of the drum. This plate is lined with asbestos on the inner side, and from it, arc barriers project down between the fingers. The current through the blowout coil sets up a strong magnetic flux which passes across the contacts. When the contacts open the current forms an electric arc, which moves toward the reader (the direction is determined by Fleming's left-hand rule). In doing so the arc is drawn out to such an extent that it becomes broken. The coil of the magnetic blowout is usually in series with the line, so that the expelling action is in direct proportion to the size of the electric arc formed.

CAM TYPE DRUM CONTROLLER.- In a drum controller of the type discussed above, the fingers slide on segments, wearing the contacts. Furthermore, the blowout coil cannot extinguish the arc fast enough to prevent some burning action, because the contacts open slowly. These difficulties are overcome in a drum type controller having cams to actuate contacts, as suggested in fig. 5-1. The cams are insulated from one another by mounting them on a square micanized shaft, which is turned by an operating handle.

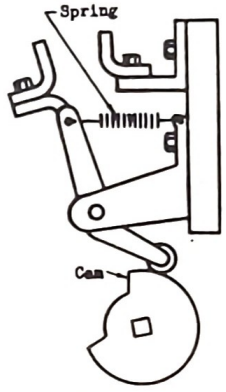


Fig. 5-1
Drum type controller with contacts which are actuated by cams

HOME WORK

1. Why is a starter necessary on D C motors ?

2. Draw a sketch showing how a series motor is connected to the starter of fig. 1.

3. What is the purpose of the holding magnet?

4. What two methods are used to connect the holding coil? What are the relative advantages and disadvantages of these methods?

5. What would be the effect of placing the starting resistance in series with the entire shunt motor instead of in the armature circuit?

6. What is the difference between a starter and a controller?

7. A 240 volt motor, which has a .3 ohm armature and a 120 ohm field, takes 50 amperes at full load. How much resistance must the starter contain to limit the starting current to 50 per cent above full load?

8. Why are cam type drum controllers more durable than the other types? Why are these types not in more general use?

AUTOMATIC CONTROLLERS.- Automatic controllers are generally used because they have a number of decided advantages over the manual type. With the manual type the operator may accelerate the motor too rapidly, resulting in the motor taking excessive current. This causes fuses to blow or circuit breakers to open. A considerable portion of the operator's time is taken from his principal duties if too much time is taken to accelerate the motor. Furthermore, the starting resistance may burn out.

With automatic controllers the starting resistance may be cut out at the maximum safe rate by means of magnetically operated switches. All the operator has to do is to press a button; the magnetic switches start the motor and bring it up to speed by cutting out the starting resistance in steps. The motor is stopped merely by pressing the stop button.

A Cutler Hammer magnetic switch is shown in fig. 6a. The essential parts of this switch are the magnet, consisting of an operating coil on an iron core, and the moving part or armature. A permanent air gap is usually made a part of the magnetic circuit to prevent the armature from sticking in the closed position after the holding coil has been de-energized. This gap may be of some non-magnetic material such as brass or bronze, as well as air.

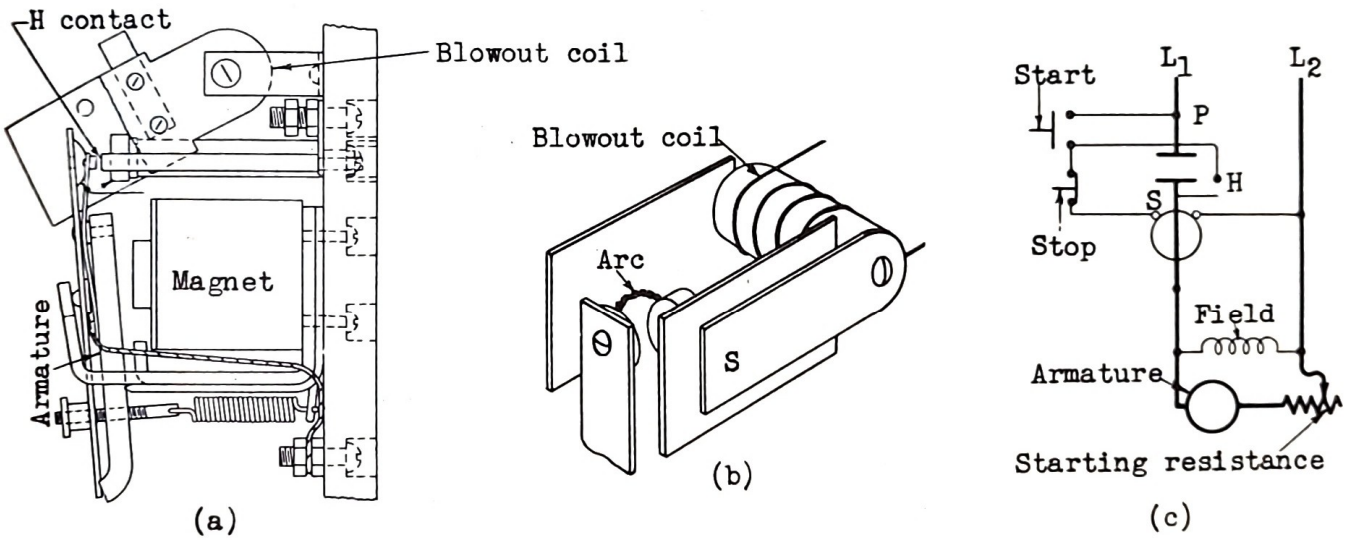


Fig. 6 Cutler Hammer magnetic switch

Since line switches usually carry a heavy current, a large arc is formed when the main contact opens. This arc is extinguished by a magnetic blowout, which in this case is made as shown in fig. 6b. The arc formed after the contacts open is forced upward, drawn out, and broken.

Magnetic switches are provided with one or more auxiliary contacts which are connected in the controlling circuit. These contacts carry small currents and require no blowout magnets.

Magnetic switches are commonly placed in the line circuit as indicated in fig. 6c. The method in which the starting resistance is cut out is not shown, as this will be considered in detail later.

When the start button is pressed (fig. 6c), a circuit is formed from L_1, through the push button and the coil of the magnetic switch, to L_2. This closes the magnetic switch and power is supplied to the motor. The magnetic switch does not open after the finger is removed from the start button, because a new circuit is provided through which the closing coil is energized. This new circuit is from L_2, through the closing coil, H contact, and stop button, to L_1.

The stop button is pressed to de-energize the closing coil. This allows the magnetic switch to drop out and the power to the motor is interrupted.

Such line magnetic switches are very popular, for the following reasons:

(1) If a switch carrying a large current is to be operated frequently, less effort will be needed and there will be less distraction for the operator if he only pushes buttons instead of operating a heavy switch. Furthermore, the opening of large current-carrying switches subjects an operator to shocks, burns, or eye injuries.

(2) If the distance from the point of control is great, a considerable saving will be effected by having a magnetic switch near the motor to carry the large currents, with only small control wires extended to a push button near the operator.

(3) At times a motor must be controlled from several points, as in driving a conveyor. This may be accomplished easily by using a line magnetic switch (see illustration in fig. 7).

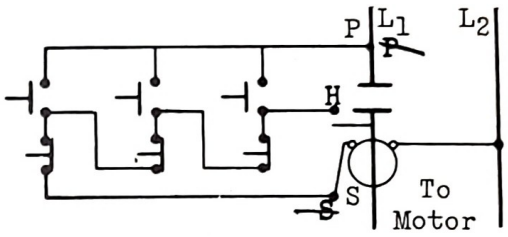


Fig. 7
Push button controls for a magnetic switch

(4) A magnetic switch may be automatically actuated by a float switch, pressure or scale switch, limit switch, etc., instead of controlling it by a push button. This eliminates the necessity of an attendant. The force that such devices can exert is not sufficient to operate switches mechanically.

A typical float switch control is shown in fig. 8. When the water raises the float above a certain level, knob 1 raises arm A and swings the weight to the left. Projector P opens auxiliary switch S. This de-energizes the holding coil and the magnetic switch opens, interrupting the power to the motor.

Knob 2 forces arm A downward when the water gets below a certain level. This swings the weight to the right and the spring closes switch S. This energizes the holding coil, which closes the magnetic switch, and the motor again starts.

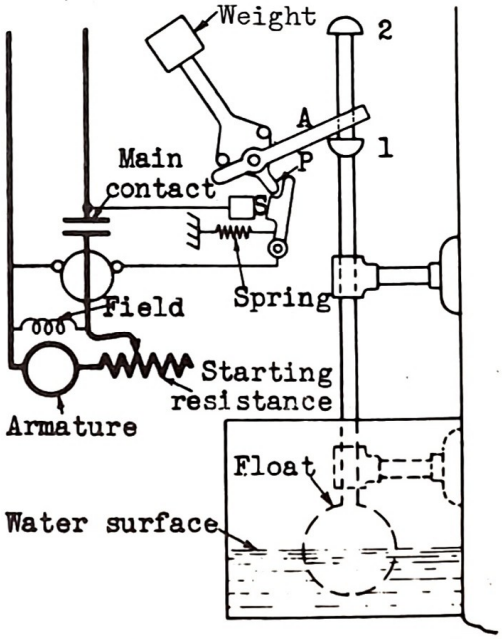


Fig. 8 Float switch control

The method of fig. 8 is used in keeping water below a certain level, as required of sump pumps. The motor starts when the water level is high and stops when it reaches a certain desired low level.

In order to maintain the pressure of motor driven pumps and compressors between certain specific limits, a pressure or scale switch is used in the pilot control. Fig. 9 shows a type of pressure switch that may be used to control the pressure of any gas or liquid. This switch may be connected so that the closing coil is de-energized when contact A opens, thus stopping the motor, or it may be connected so that the motor starts as soon as contact B is made.

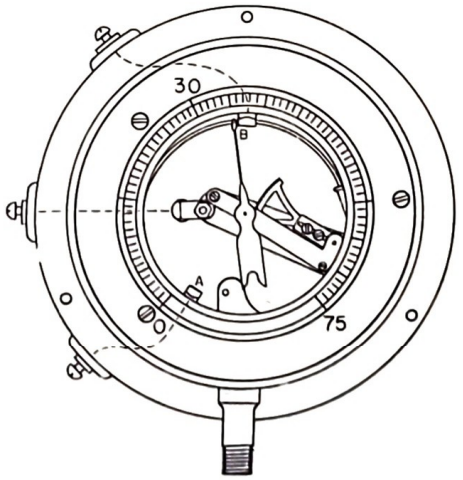


Fig. 9 Pressure switch

To prevent the over-travel of doors, cranes, elevators, etc., limit switches are connected in the control circuit. Such switches not only stop the motor but provide means of starting it in the reverse direction. The method by which these switches are connected in the control circuit will be considered in discussing automatic starters.

A thermostat or thermocouple control is used for starting and stopping a motor when the temperature of a liquid or gas reaches a certain point.

The thermostat control consists of two metals welded together, the two metals having different coefficients of expansion (fig. 10a). This bi-metal is fastened at one end so that the free end will bend slightly to one side under the influence of heat and make contact with a fixed post (fig. 10b), thus completing the circuit of the closing coil.

The magnetic switch in the motor circuit must be controlled indirectly when a thermocouple is used, as illustrated in fig. 11. When the temperature of the thermocouple reaches a certain point, sufficient current is established to close the midget relay. This completes the circuit of the coil of switch M, closing it and starting the motor.

The control of fig. 11 is used when it is desired to control a motor by a light, except that the thermocouple is replaced by a Photronic tube (fig. 12). Electrons are emitted when light strikes the cathode surface in the Photronic tube, flowing to the anode and then through the external circuit. This causes the relay and switch M to close, thus starting the motor.

Reverse operating conditions may be obtained in figs. 11 and 12 by using a midget relay that is normally closed when no current flows through its coils and opens when it is energized.

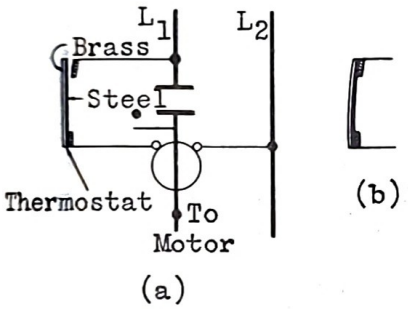


Fig. 10
Control by thermostat

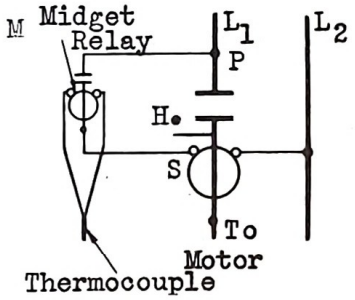


Fig. 11
Control by thermocouple

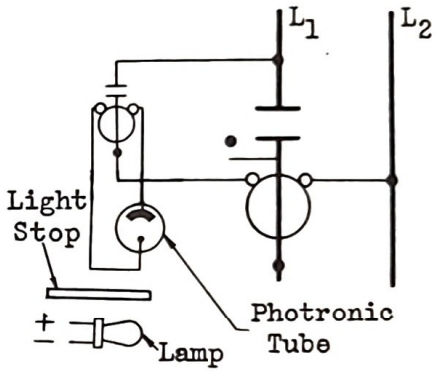


Fig. 12
Control by light

(5) With the magnetic switch it is easy to provide low voltage and overload protection.

LOW VOLTAGE PROTECTION.- If the switch has a three wire control, as in fig. 6, it automatically opens upon voltage failure, and remains open after the voltage is restored until the start button is again pressed. This is known as low voltage protection. Such protection is essential on all machines that may cause personal injury if they start unexpectedly.

In some cases, as with motors driving blowers and pumps, it is desirable that the motor start automatically as soon as the voltage is back to normal. A motor provided with such a control is said to have low voltage release protection. Such protection is obtained by using a two wire control, as shown in fig. 13.

OVERLOAD PROTECTION.- Overload protection may be obtained by means of fuses and magnetic or thermal overload relays. Fuses have commonly been used because of low cost, but the development of low price overload relays is making popular this type of overload protection, especially on large controllers.

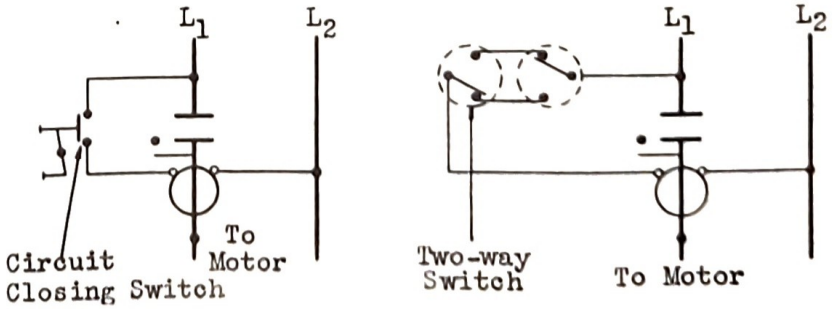


Fig. 13 Low voltage release control

Magnetic overload relays, which are usually connected in the control circuit as shown in fig. 14, are generally made in two types. One type provides an instantaneous trip and the other a time delay trip. The instantaneous trip relay (fig. 14a) must be set so that it will not trip because of the starting current, but will trip only when the load current becomes abnormally high. The time delay trip is similar to the instantaneous trip except that a dash pot is added to provide the time delay feature. This dash pot prevents the relay from tripping because of momentary inrushes, but if a sustained overload occurs it will trip after a brief period.

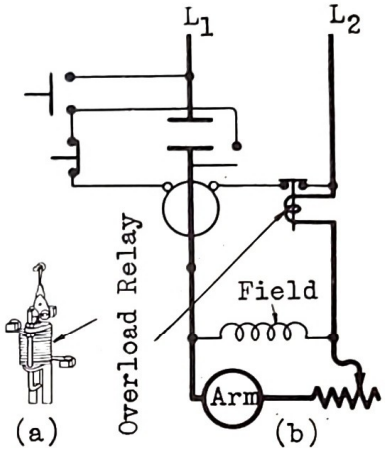


Fig. 14
Overload relay connection

The thermal overload relay is made somewhat like a thermostatic control as it consists of two metals of different coefficients of expansion welded together. This bi-metal is placed near a heating element through which the current to the motor passes (fig. 15). One end of the bi-metal is fixed and the other end is free to bend when the temperature changes. When a heavy overload persists long enough to raise the temperature of the motor to a dangerous value, the bi-metal is heated and bends as indicated by the dotted lines in fig. 15. This opens the circuit at A, which de-energizes the coil of the magnetic switch.

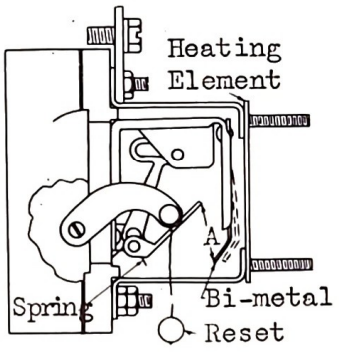


Fig. 15 G E thermal overload relay

(6) Protection against an open or shorted shunt field may be provided with the magnetic switch. This protection, which is especially essential on grinding wheels, is affected with the use of a field relay (fig. 16a) connected in the circuit as shown in fig. 16b. Coils A and B, which are in series, are connected in series with the shunt field. The auxiliary contact C is inserted between the H contact of the magnetic switch and the H terminal of the push button. When the start button is pressed the magnetic switch is closed and current is supplied to the motor. A small current also passes through the field and coils A and B. The magnetizing force of coil A is sufficient to close contact C, which provides a circuit from L_1, through the H contacts and coil M, to L_2. The flux produced by coil A holds the magnetic switch closed. The motor will not race if the field becomes open, because the flux of coil A becomes zero and contact C opens. This opens the circuit of coil A, and the magnetic switch opens.

If the field becomes shorted (or grounded), coil B produces a flux of sufficient strength to open contact C by attracting its armature. This again stops the motor from racing.

Motors should not be permitted to race, even for a short time, because at abnormally high speeds they are likely to damage themselves and the driven machinery by the action of centrifugal force.

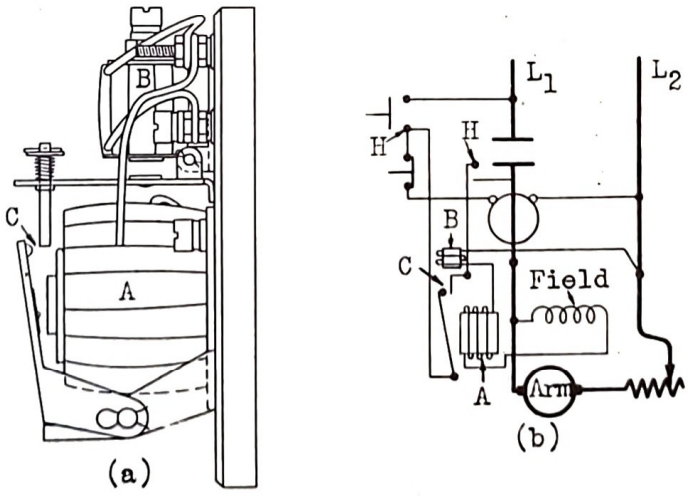


Fig. 16 Field relay connection

It was previously mentioned that several methods may be employed to gradually cut out the starting resistance. These are: (1) counter electromotive force (usually written counter e m f) method, (2) current limit method, (3) time element method.

COUNTER E M F METHOD.- A simple diagram illustrating the principle of the counter e m f method of cutting out one step of starting resistance is shown in fig. 16a. The magnetic switch, which is controlled by a push button in the manner already explained, is represented at 1. A switch which serves to cut out the starting resistance is represented at 2. This switch is usually called an accelerating contactor, and in the Ford starter is constructed as shown in fig. 16b.

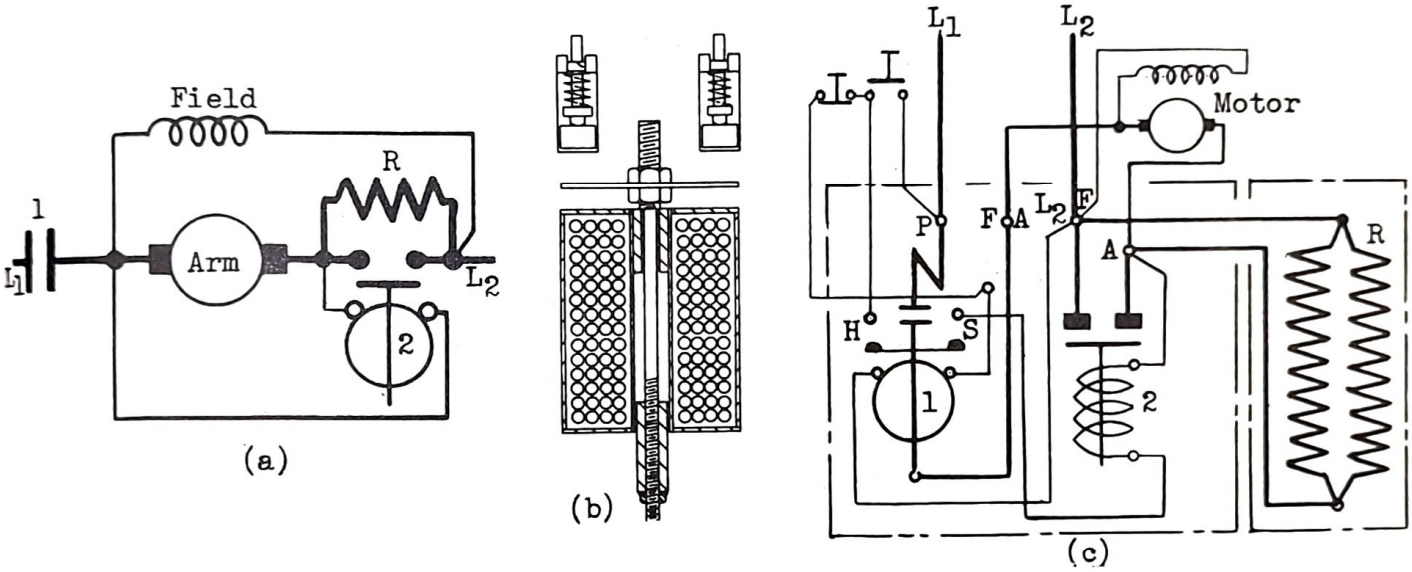


Fig. 16 Counter e m f method of accelerating motors

The motor accelerates after switch 1 is closed, causing the counter e m f and therefore the terminal voltage of the armature to increase. Since the coil of contactor 2 is connected across the armature, its current will increase with the counter e m f. By properly adjusting the air gap of contactor 2, it will close at a fixed voltage, and thus short out resistance R which is in series with the armature. For a 240 volt machine, the contactor closes when the voltage at the brushes reaches about 200 volts.

In the simple arrangement of fig. 16a, contactor 2 will not open immediately when switch 1 is opened, but will be held closed by the counter e m f induced in the armature. The counter e m f must drop to about 20% of the full load voltage in order to release the contactor. If the magnetic switch is opened and then closed again before the armature speed has reduced to 20% of its full speed value, contactor 2 will remain closed. This will cause the armature to take a high current, and perhaps also severely jar the driven machinery. In order to eliminate this possibility, another contact is usually provided on the magnetic switch, which opens the circuit to the coil of contactor 2 as soon as switch 1 is opened. This is illustrated in fig. 16c, which shows a wiring diagram of the Ford starter. The scheme shown in fig. 16a, however, is used fundamentally in all counter e m f starters.

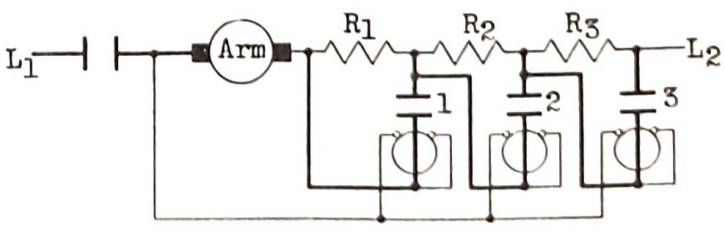


Fig. 17
Cutting out the starting resistance in three steps by the counter e m f method

It is possible to arrange several contactors to close at different armature voltages (fig. 17). Thus the starting resistance may be cut out in several steps.

The scheme used in the counter e m f starter manufactured by the Cutler-Hammer Company is shown in fig. 18a. This starter differs from the one discussed previously in that it has only one auxiliary contact on the magnetic switch, and the accelerating contactor has a compound coil. When the start button is pressed (see fig. 18b), coil A is connected directly across the line, closing contactor 1. After the finger is removed from the start button, section B of the compound coil is connected in series with coil A. This reduces the power required to hold switch 1 closed, and the magnetizing action of section B aids section C, which closes contact 2 when the armature voltage reaches a selected value.

Coil A is de-energized when the stop button is pressed, allowing switch 1 to open and interrupting the current to the motor.

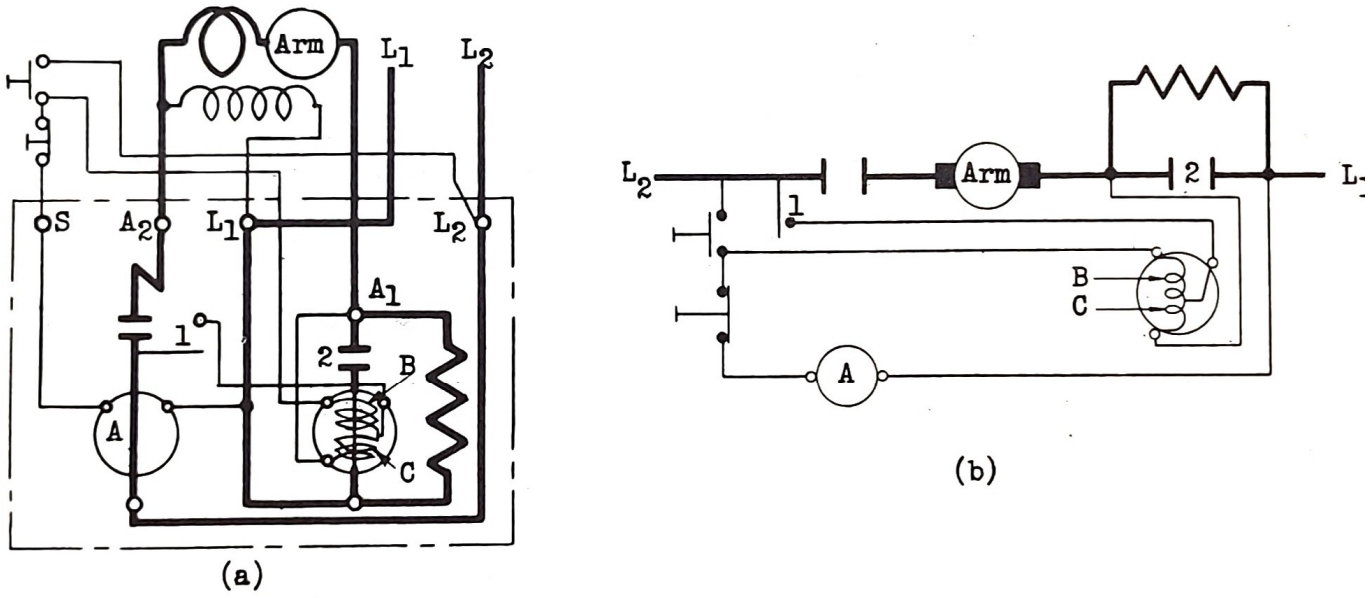


Fig. 18 Cuttler-Hammer counter e m f starter

Counter e m f starters are objectionable where considerable variation in the line voltage exists. When the line voltage is above normal, the accelerating contactor closes too soon, and when far below normal the accelerating contactor at times does not close. This type of starter has the advantage that it is simple in structure and requires few auxiliary contacts.

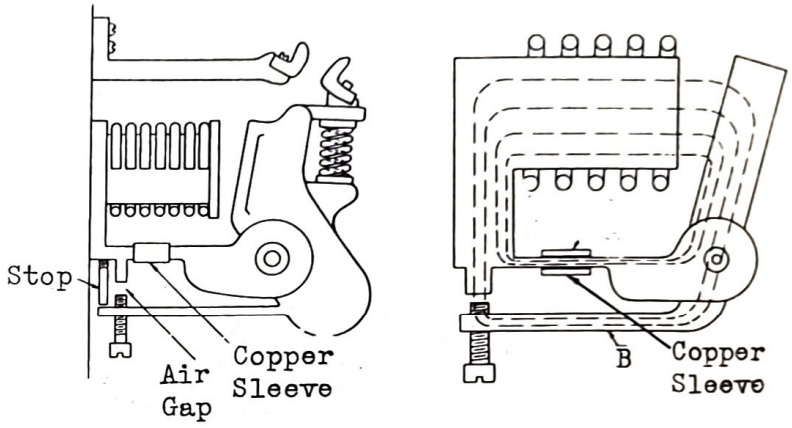
CURRENT LIMIT METHOD.- The two principal methods of obtaining current limit acceleration are by (1) series lockout contactors or (2) series relays.

(1) SERIES LOCKOUT CONTACTORS.- The series lockout contactor is designed so that it will hold open when the current through its coil exceeds a set value, but will close promptly as soon as the current falls below this value. There are two general types of such contactors, one having a single coil and the other having two coils.

SINGLE COIL LOCKOUT CONTACTORS.- The single coil contactor depends for its operation upon the saturation of a portion of the magnetic circuit. A contactor of this type is shown in fig. 19a. Its operating characteristic is secured by providing two magnetic circuits, one through the yoke A and one through the tail piece B (fig. 19b).

The flux through A tends to close the contactor and the flux through B tends to hold it open. The cross section of A is very small. Hence, when the coil current exceeds the set value, A becomes saturated and a large amount of flux passes through B, holding the contacts open. When the current falls below the set value, the flux passes almost entirely through A, because section A is no longer saturated and the air gap at the end of the tail piece provides considerable reluctance in the B circuit. Thus the contactor closes. In closing, the lockout air gap is increased and the air gap between the armature and coil is decreased. This causes the contacts to close rapidly, and then hold together with considerable force.

The contactor may be adjusted to close at any suitable current value by changing the length of the air gap between the end of the tail piece and the yoke.



(a) (b)

Fig. 19 Series lockout contactor

It may appear that the contactor will close while the coil current is increasing, because A must become saturated before the flux begins to build up in B. This difficulty is overcome by the copper sleeve around A. With a rising coil current a voltage is induced in the sleeve, causing a flow of current in the sleeve. This current sets up a flux which prevents the main flux from passing through A, thus causing it to first build up in B.

A series lockout contactor, which operates fundamentally on the same principle as that of fig. 19a, is shown in fig. 20. With a high coil current, considerable flux passes through B, holding the contactor open. With a current below the set value, little flux passes through B, thus permitting the contactor to close. As in fig. 19, the yoke in fig. 20 must be surrounded by a copper sleeve.

A simple starter with series lockout contactors is shown in fig. 21. At the instant that the magnetic switch is closed by pressing the start button, the shunt field is connected directly across the line, and all of the resistance is connected in series with the armature. Contactor 1 closes as soon as the counter e m f reduces the armature current to the value at which contactor 1 is set to function. This cuts out R_1 and inserts the coil of contactor 2 in the armature circuit. As the speed of the motor increases further, the current decreases sufficiently to allow contactor 2 to close, thus connecting the armature directly across the line.

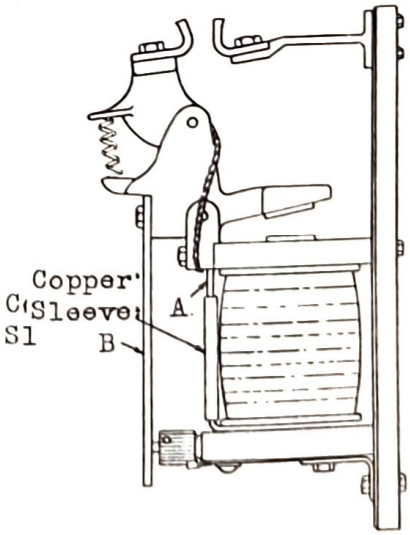


Fig. 20
A lockout contactor similar in principle to the one in Fig. 19

Fig. 22 shows a series lockout contactor different in form from those previously discussed. It is of the plunger type. The coil is of heavy wire, because it must carry the armature current, and surrounds a brass tube, within which the plunger P moves freely. The stem of plunger P extends into the soft iron tube S, which may be screwed in or out to vary the length of air gap G. A circular brass plate is attached to the top of the plunger, with a non-magnetic pin. This contacts with two brushes when the plunger is forced up.

A short iron tube, which extends nearly to the head of the plunger, surrounds the non-magnetic pin and thus establishes another air gap A. The coil is enclosed in an iron case C, providing an external path of low reluctance for the returning flux.

The operation of this contactor will be considered in connection with the simplified diagram shown in fig. 23. When a current flows through the coil, the magnetic lines pass through air gap A and tend to raise the plunger. If the current is high, two magnetic paths are formed at the lower end of the plunger. One path of the flux enters the stem at right angles to the direction in which the plunger moves, thus making this flux ineffective in producing a downward pull. Because of the stem becoming saturated, another path of flux is set up through air gap G (fig. 23a). The flux through this path and the weight of the moving parts prevent the plunger from moving upward.

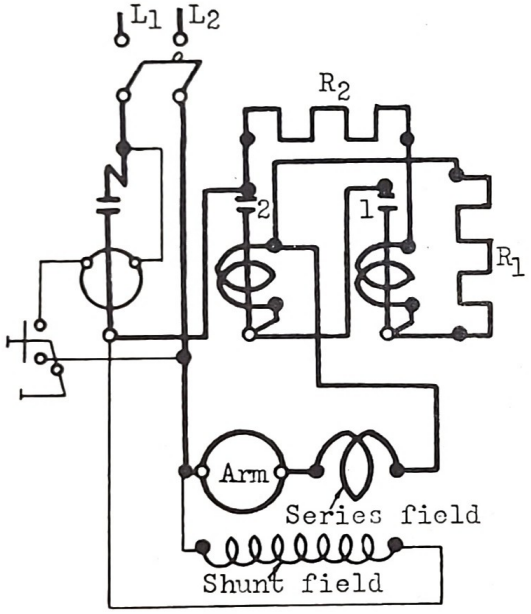


Fig. 21
Simple starter employing series lockout contactors

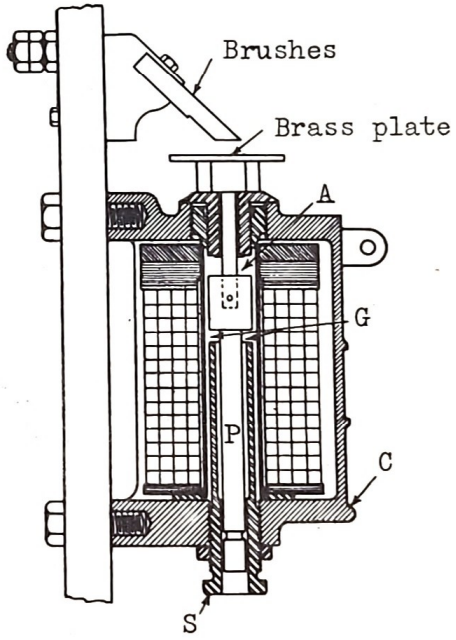
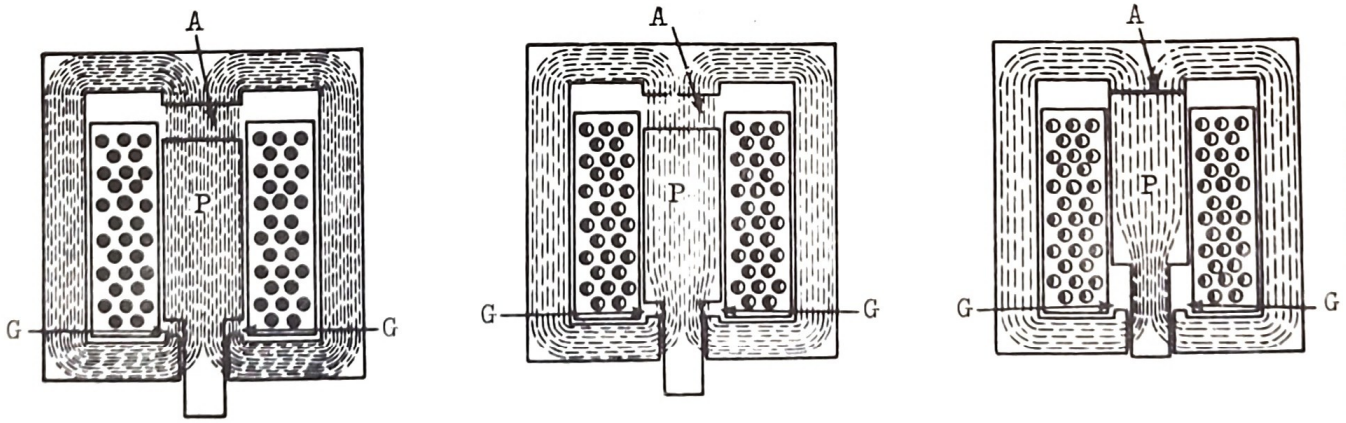


Fig. 22 Plunger type of series lockout contactor



(a) High current (b) Low current (c) Low current

Fig. 23 Magnetic paths of the E C & M series lockout contactor

When the coil current drops below a set value, the stem will no longer be saturated because less flux will be established. Thus nearly all the flux will enter the stem and little will pass through air gap G (fig. 23b). As a result, the upward pull due to the flux through air gap A will exceed the downward pull, which in this case is only the weight of the moving parts, and the plunger will move upward and close the contacts.

In fig. 22, air gap G is lengthened if plug S is screwed out, allowing the contactor to close at a larger value of current. Air gap G is shortened if S is screwed in, allowing the switch to close at a smaller value of current.

The wiring diagram of a starter with E C & M type series contactors is shown in fig. 24. After the knife switch is closed, the magnetic switch may be closed by pressing the start button. After this button is released, resistance R is inserted in series with coil A. This resistance reduces the power supplied to A, which need not be large to hold the magnetic switch closed. On closing the magnetic switch, the field is connected across the line and current flows from L_1, through the series field and armature, through the entire starting resistance and the coil of contactor 1, to L_2. Although current flows through the coil of contactor 1, it will not close until the counter e m f has reduced this current to the value for which it is set.

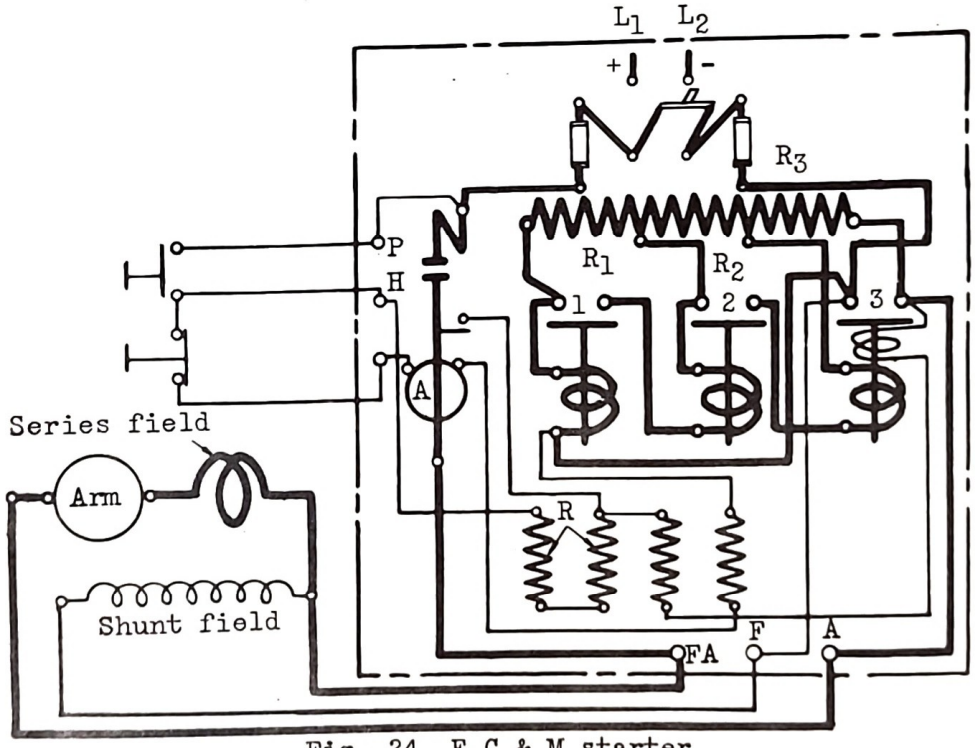


Fig. 24 E C & M starter

When contactor 1 does close, R_1 is short-circuited and the current flows through the series field and armature, through R_3, R_2, and the coils of contactors 2 and 1, to L_2. The increase in current due to the closing of contactor 1 causes contactor 2 to be locked out. Contactor 2 closes as soon as the counter e m f has reduced the current to a value for which it is set, shorting out R_2 and inserting the coil of contactor 3 in the circuit. Contactor 3 closes as soon as the current drops to a value for which it is set, shorting out R_3 and connecting the series field and armature directly across the line. Contactor 3, on closing, short-circuits its closing coil and those of the other contactors. Contactors 1 and 2 drop open, but 3 is held closed by the small shunt coil near the top of the contactor. This shunt coil is just strong enough to hold 3 closed after the series coil has closed it. The motor is stopped merely by pressing the stop button.

DOUBLE COIL LOCKOUT CONTACTOR.- Another type of current limit contactor is shown in fig. 25a. It has two coils which are connected in series with the armature, the upper coil closing the contactor and the lower one locking it open. The iron surrounding the closing coil is worked near saturation, so that the closing force is strong at a low current and increases slightly as the current increases. The iron surrounding the lower coil is not saturated, so that the pull exerted by this coil increases rapidly with an increasing current. The pull of each coil varies with the current in the manner indicated by the curves in fig. 25b. When the current exceeds the value at A, the lockout pull is stronger and the contactor remains open. When the current drops below A, the closing force predominates and the contactor is closed. The contactor is made to operate at different values of current by adjusting screw S.

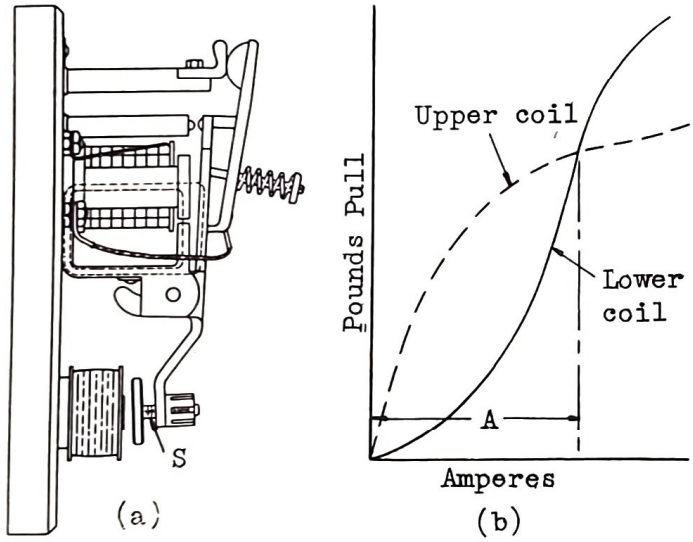


Fig. 25 Lockout contactor with two series coils and characteristic curve

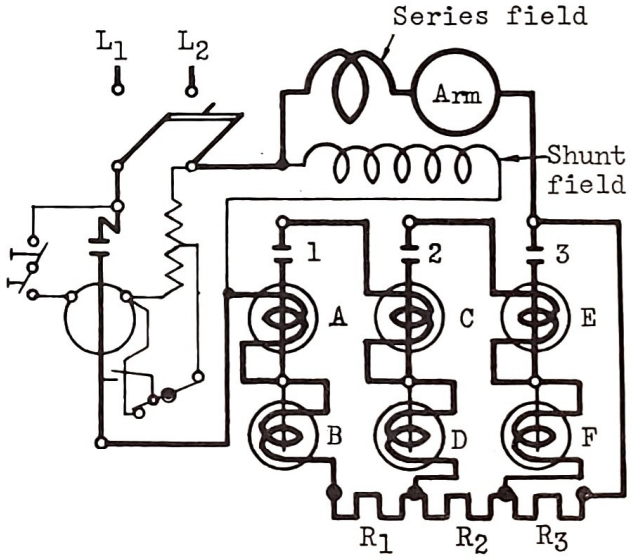


Fig. 26 Starter that employs current limit contactors with two series coils

The diagram of a starter that employs this type of contactor is shown in fig. 26. After the knife and magnetic switch are closed, a high current flows from L_1, through coils A and B, through all the starting resistance, through the armature and series field, to L_2. At the same time the shunt field is connected across the line. Contactor 1 closes as soon as the current reduces to a value for which this contactor is set, shorting out B and R_1, and providing a current circuit through the closing coil A and through coils C and D of contactor 2. Contactor 2 closes as soon as the current again reduces sufficiently, shorting out D and R_2 and providing a circuit through coils C, E, F, and R_3. All the starting resistance is cut out as soon as contactor 3 closes, connecting the motor across the line.

Another type of double coil, current limit type of contactor is illustrated in fig. 27. It has a shunt coil for closing the contactor and a series coil under the tail piece for locking it open. The shunt coil exerts a constant pull because it is connected across the line. The series coil, being in series with the armature, produces a pull that varies with the armature current. When the motor starts, the high current through the series coil causes a lockout force to exceed by far the closing force.

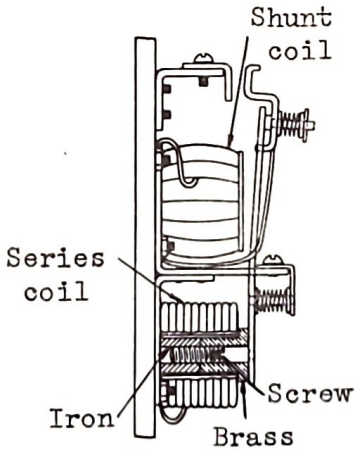


Fig. 27 Lockout contactor with a shunt and series coil

The lockout force decreases as the current reduces, until finally the closing force predominates and closes the contactor. This contactor is set to close at a given current by adjusting the set screw located at the center of the series coil.

The wiring diagram of a starter which employs this type of contactor, manufactured by the Monitor Controller Company, is shown in fig. 28. In this starter note that the magnetic switch has two auxiliary contacts, serving the same purpose as those on the magnetic switch of the Ford counter e m f starter. Contact H completes the circuit to the holding coil after the push button is released. Contact 1 disconnects coil A from the armature when the motor is stopping. Thus if the start button is pressed again before the motor speed reduces sufficiently, the armature will not be connected directly across the line, but will be in series with the starting resistance. When the magnetic switch is closed, the high current flows from L_1, through the magnetic switch, resistance R, and series coil, through the armature and series field, to L_2. The contactor closes as soon as the current decreases to the value for which the contactor is set. This shorts out resistance R, connecting the armature with the series field directly across the line.

The main disadvantage of this starter is that the accelerating contactor connects the motor directly across the line if the starting resistance is open. To overcome this, the coil may be connected across the brushes as shown by the dotted lines, with contact 1 removed.

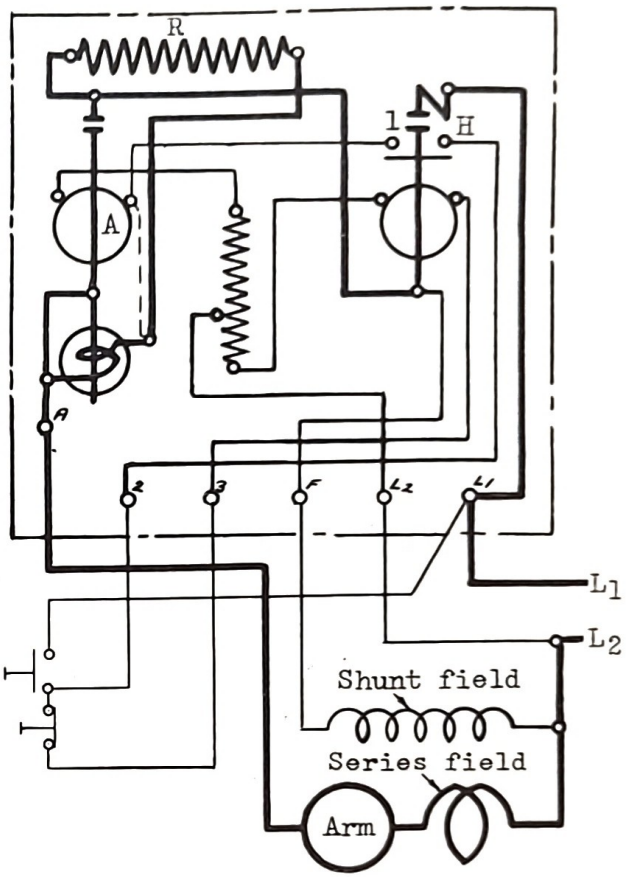


Fig. 28
Monitor starter for 1-3 H P motors

(2) SERIES RELAYS.- A starter using series relays is generally more complicated than other current limit types, as a relay must be provided for each step of resistance, in addition to contactors, and electrical or mechanical interlocks are required.

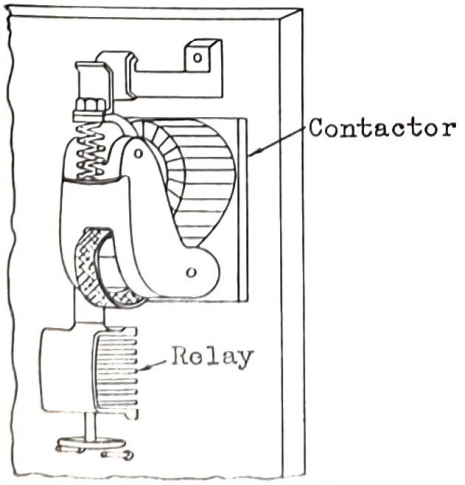


Fig. 29 Contactor with a current limit type relay

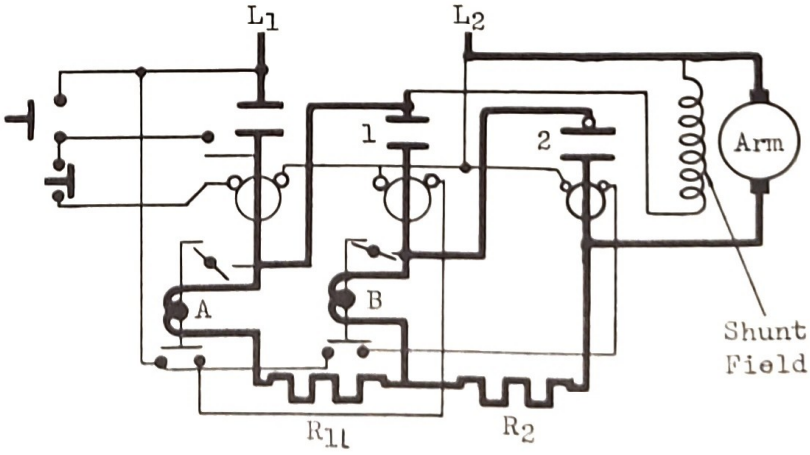


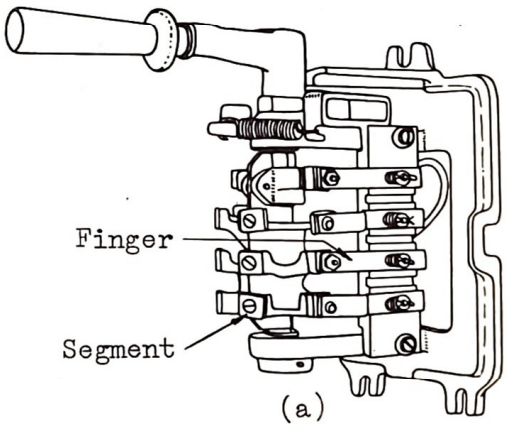
Fig. 30 Wiring diagram of a starter employing current limit type relays

Fig. 29 shows a contactor and relay. The relay is normally closed by the force due to gravity. However, the magnetic force produced by the coil holds it open until the current has decreased to the set value. The relay is sometimes mechanically interlocked with the contactor so that it is held open until the contactor closes.

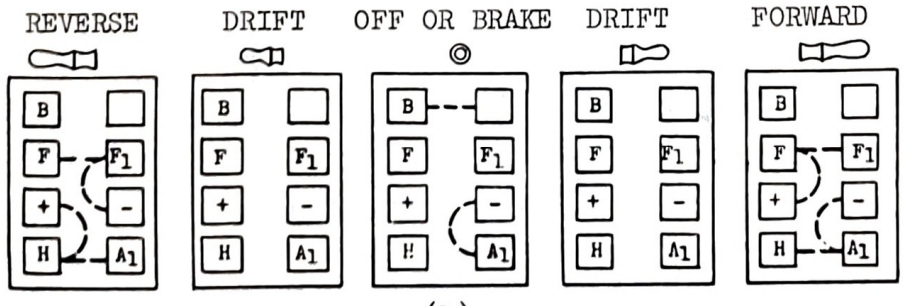
A starter employing series relays is shown in fig. 30. At the instant that the magnetic switch is closed, a high current flows from L_1, through the magnetic switch and relay A, through both resistances and armature, to L_2. At the same time, the magnetic switch releases the plunger of relay A so that its contacts may close. However, the high current through this relay holds its contacts open until the current drops to a value for which it is set to close. The contacts of relay A close as soon as this current value is reached, causing contactor 1 to close because the circuit of its closing coil has been completed. This shorts out relay A and R_1, providing a current path through contactor 1 and relay B. Relay B closes as soon as the current reduces to a value for which it is set to operate, completing the circuit of the coil of contactor 2. Contactor 2 closes, shorting out relay B and R_2, connecting the motor across the line.

GENERAL CHARACTERISTICS OF CURRENT LIMIT STARTERS.- Current limit starters are popular because of their simplicity. These starters require practically no interlocks (with the exception of those with series relays), and are not likely to cause trouble. They are easily adjusted, even for extreme conditions. However, current limit starters may be undesirable for loads that are extremely heavy at starting, because their contactors may fail to short out all of the starting resistance. Furthermore, some of these starters are not suitable for handling very light loads, because the contactors will not remain closed.

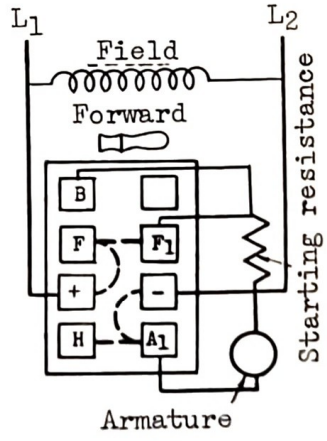
DYNAMIC BRAKING AND REVERSING.- Some industrial operations require the use of controllers that provide dynamic braking and reversing. The kind of operating switch required by one type of such a controller is shown in fig. 31a. The sequence in which the contacts are made is shown in fig. 31b. The line wires are connected to the + and - terminals. When the handle is in the "reverse" position, H and A_1 are positive while F and F_1 are negative (see fig. 31b). On moving the handle to the "forward" position, F, F_1 and H, A_1 exchange polarities. If an armature is connected between A_1 and F_1 (through a starting resistance), as indicated in fig. 31c, the current through it, and therefore the direction of rotation, will reverse as the handle is shifted from "reverse" to "forward."



(a)



(b)



(c)

Fig. 31 Reversing control switch with dynamic brake

Hence, this switch is fundamentally a reversing switch, and may be connected in conjunction with any starter.

If the handle is brought from a "running" to a "drift" position, the armature is disconnected from the line, and the motor is brought to a standstill by the load.

If the handle is brought from the "running" to the "off" or "brake" position, contacts are made which connect terminals A_1 and B (fig. 31b), placing the starting resistance directly across the armature terminals. The rotation of the armature under the influence of the excited shunt field causes a voltage to be generated, sending current through the starting resistance. As a result, the machine functions as a loaded generator and develops a retarding torque which rapidly slows down the motor, bringing it to a standstill.

Fig. 32 shows a reversing controller manufactured by the E C & M Company. In this controller the starting resistance is automatically cut out of the armature circuit as explained in the discussion relating to fig. 24.

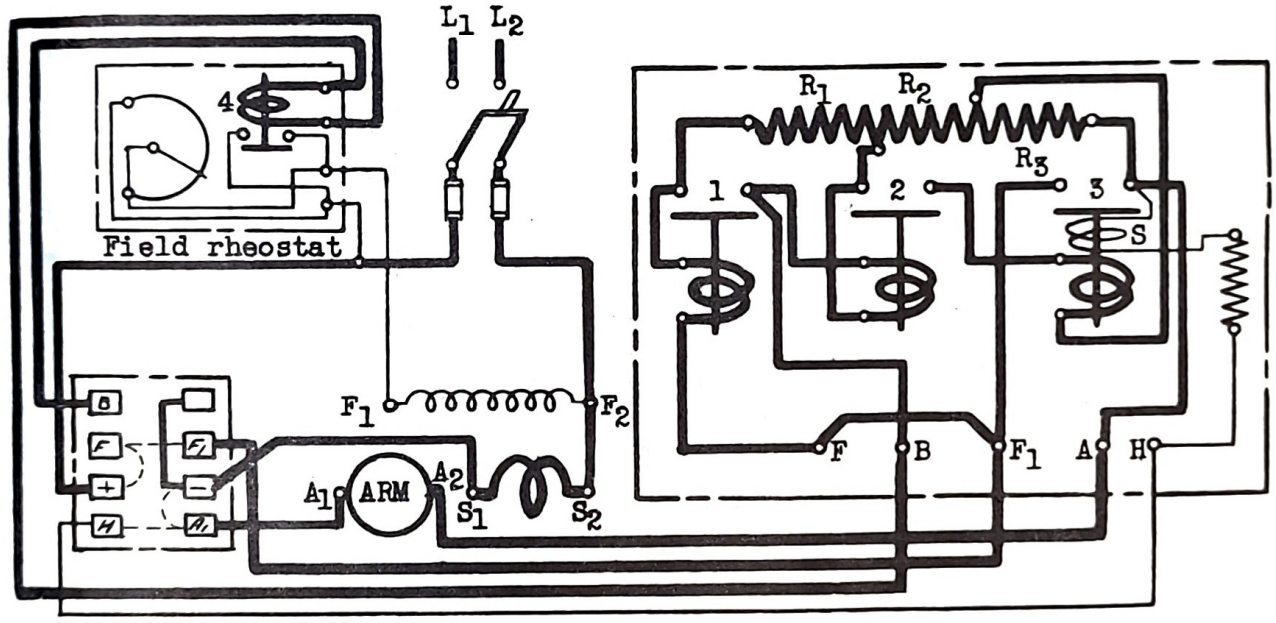


Fig. 32 Variable speed motor controlled by a reversing and dynamic braking controller

The shunt field is connected across the line, through the field rheostat, when the knife switch is closed. With the control switch in the "forward" position, the main circuit is from L_1 to terminal F_1 on the operator switch, through all the starting resistance and armature, through the control switch to terminal -, and through the series field to L_2. Contactors 1, 2, and 3 close in sequence as the armature current decreases, connecting the motor across the line. The other contactors open as soon as contactor 3 closes, because their coils are short-circuited. Contactor 3 is held closed by the shunt coil s.

Dynamic braking is effected by bringing the handle of the control switch from the "forward" to the "off" position. Segments in the control switch connect terminals A_1 and B together, placing sections R_2 and R_3 of the starting resistance across the brushes. This circuit provides dynamic braking action, causing the motor to rapidly slow down. As it slows down, the generated voltage decreases and the current through the resistance therefore decreases, tending to reduce the braking torque. The contactors, on closing, increase the braking action as the motor slows down. When the current drops to the value for which contactor 2 is set, this contactor closes and shorts out R_2, leaving R_3 in the circuit.

This increases the current and the braking torque. Contactor 3 closes when the current drops to the value for which it is adjusted, shorting out R_3. This short-circuits the armature and quickly brings the machine to a final stop. Relay 4 short-circuits the field rheostat, assuring a full field during the dynamic braking period.

Dynamic braking likewise occurs when the handle is brought from the "reverse" to the "off" position.

OTHER HOOKUPS OF THE OPERATOR SWITCH.- In the discussion relating to fig. 31, it was suggested that an operator switch may, in general, be used with any type of starter. Its use with two types of starters previously discussed is illustrated in fig. 33.

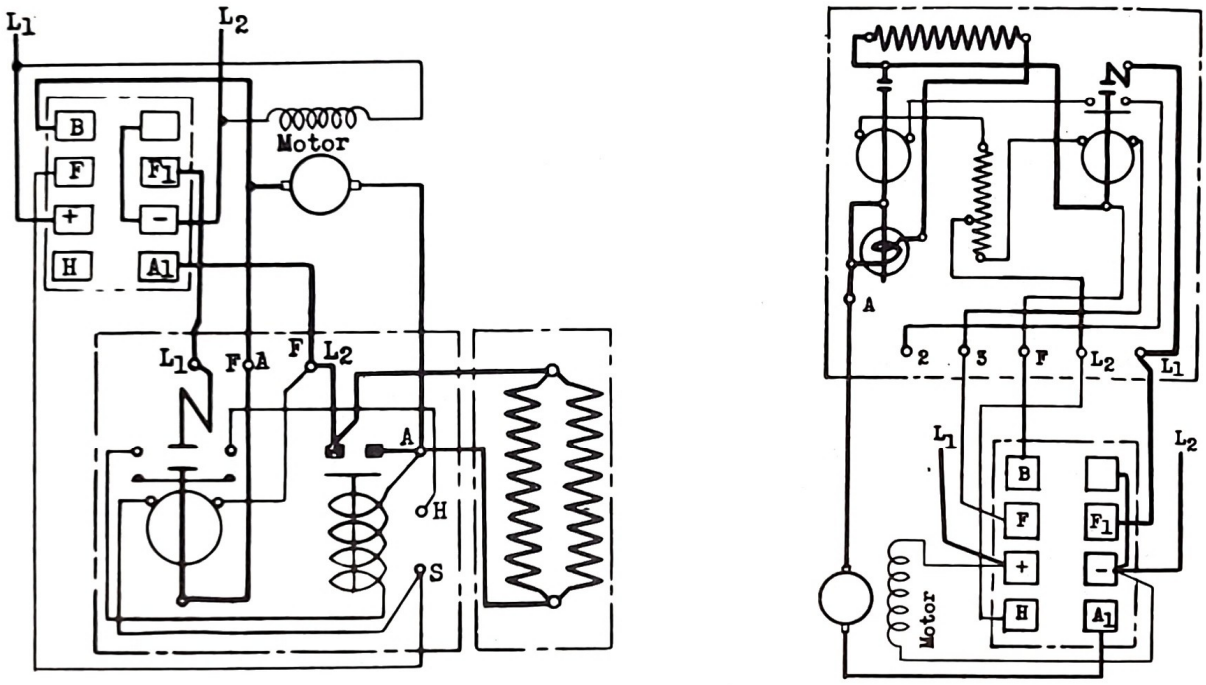


Fig. 33 Starters controlled by an operator switch

HOME WORK

1. Explain why a counter-electromotive force starter is so-named.

2. Why cannot contact S in fig. 16 be omitted?

3. Describe briefly the different types of current limit contactors.

4. In a current limit type controller, when the last contactor closes it short-circuits all the contactors and is held closed by a small auxiliary coil. Why is this desirable?

5. What is meant by dynamic braking, and how is it accomplished?

6. Why are the shunt fields in fig. 33 connected directly across the lines?

7. Make a diagram showing how the starter of fig. 18 may be controlled by an operator switch.

TIME ELEMENT METHOD.- If a motor, equipped with a type of starter previously discussed, is so heavily loaded that it does not start when all the starting resistance is in the armature circuit, the accelerating contactors will not short-circuit the starting resistance. In this case the starting resistance is likely to burn out unless the overload protection opens the load circuit. If a motor is equipped with a time element controller, the starting resistance is cut out in a definite time, regardless of the load, as long as this load does not exceed the value for which the overload is set.

There are three important methods of obtaining definite time limit acceleration. These are: (1) By dash pot, or by a pendulum arrangement similar to the escapement of a clock; (2) By a pilot motor; (3) By inductive time limit.

DASH POT TIMING.- Fig. 34a shows a starter with an accelerating mechanism of the air dash pot type (an oil dash pot could have been used). In this starter the time of acceleration may be varied over a wide range by adjusting the air inlet valve. This valve is usually adjusted so that the motor will accelerate properly under the most severe load conditions. The time of acceleration for light loads is therefore longer than is necessary.

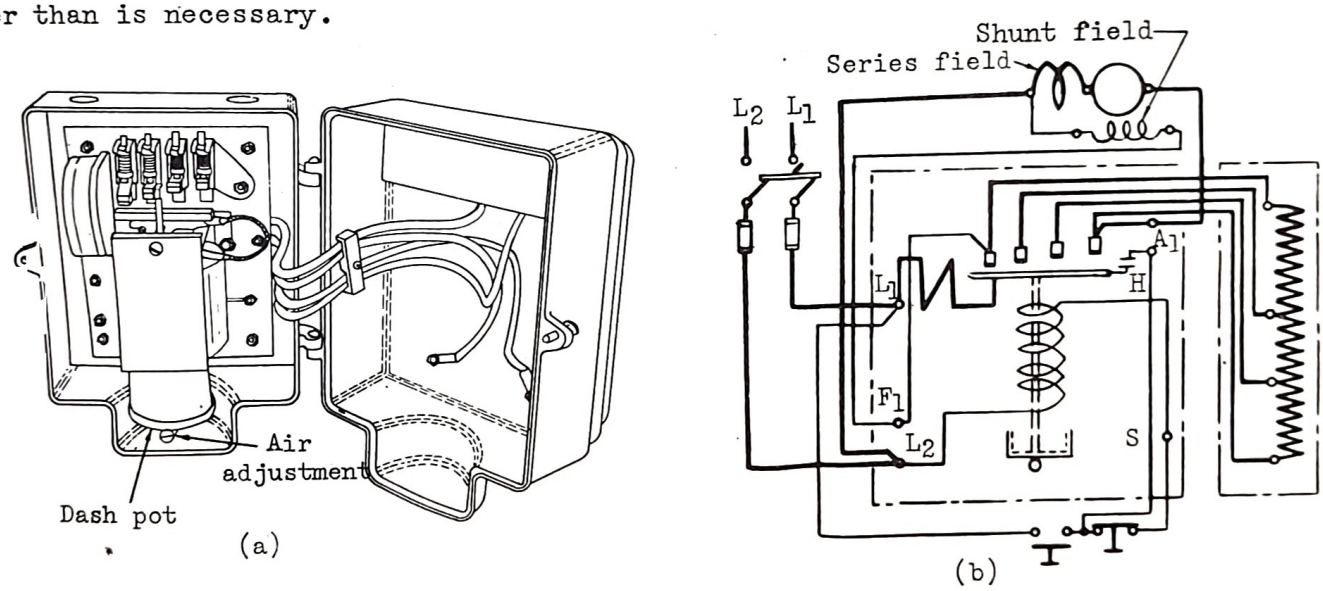


Fig. 34 Ford starter of the dash pot type

The wiring diagram of this starter is shown in fig. 34b. The solenoid causes the bar mounted on the plunger to engage successively with four fingers. A step of resistance is cut out as each finger is engaged. The dash pot prevents the solenoid from driving the plunger up too rapidly, as this would cause the motor to be accelerated too fast.

The starter functions in the following way. After the main switch is closed and the start button is pressed, a circuit is completed from L_1, through the push button and solenoid, to L_2. The current through the solenoid causes the plunger to move slowly upward, the motion being retarded by the dash pot. First, the horizontal bar closes contact H, causing the solenoid to remain energized after the start button is released. Contact H and all the fingers are under spring tension; thus the horizontal bar continues to move upward, cutting out the remaining two steps of starting resistance and connecting the motor to the line.

The coil circuit is opened when the stop button is pressed, and the horizontal bar drops instantly from the fingers.

The main disadvantage of this starter is that the dash pot sometimes gives trouble. If an air dash pot is used, the air valve is likely to become clogged with dust and thus change the time of acceleration. Furthermore, the leather dries if the air dash pot is not oiled occasionally, and little or no vacuum is produced when the plunger moves upward. The timing of oil dash pots varies considerably with changes in temperature, and no oils are available which entirely eliminate this undesirable feature.

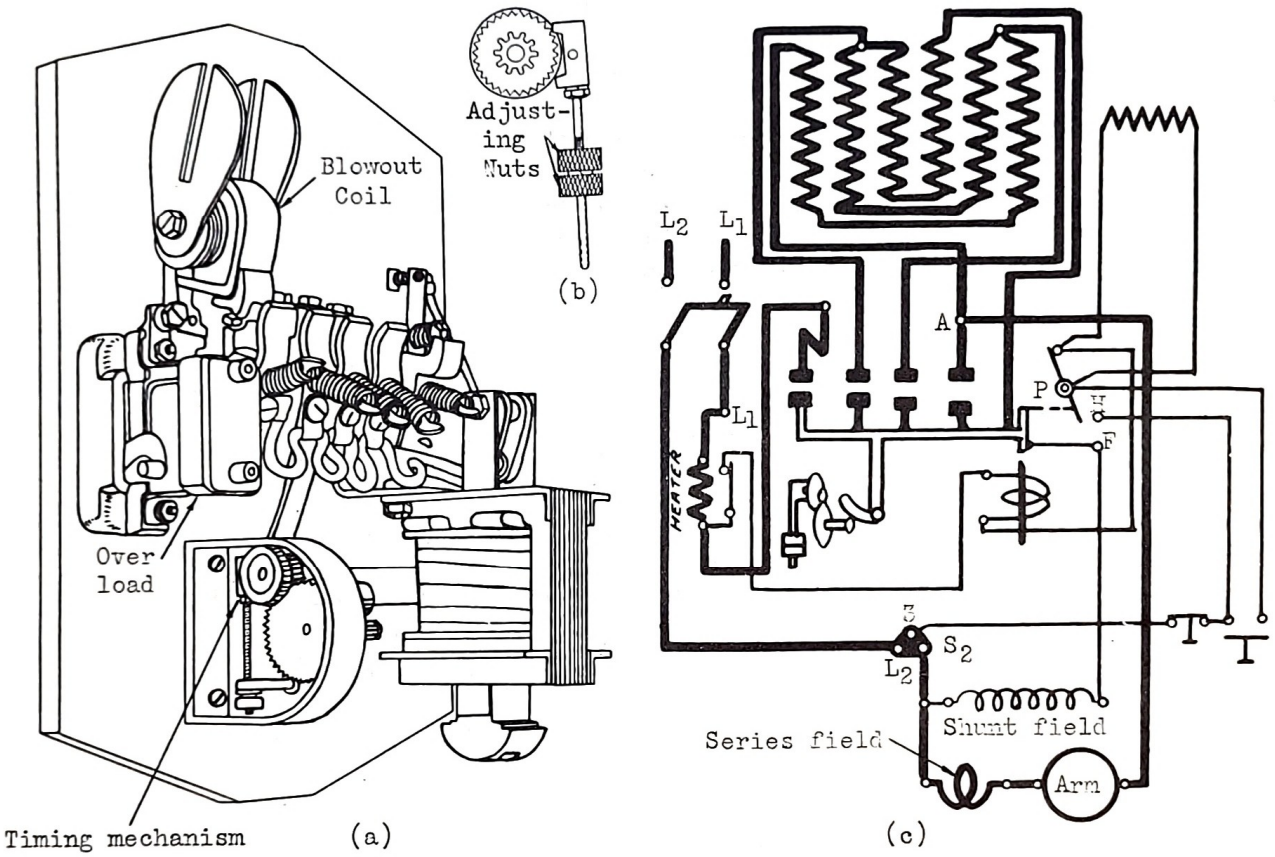


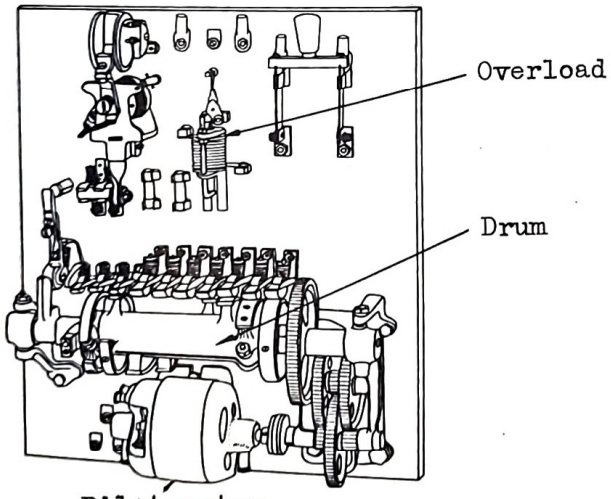
Fig. 35 Pendulum type starter manufactured by General Electric Company

TIME ELEMENT STARTER WITH PENDULUM TIMING.- A starter provided with a pendulum type timing mechanism is shown in fig. 35a. Its principle of operation is much the same as that of the dash pot starter (fig. 34). It has a multicontact magnetic switch consisting of one line contact and three accelerating contacts, all operated by a single solenoid. When the solenoid is energized, the line contact closes at once but the accelerating contacts close in sequence, each after a definite time interval. The timing mechanism, which governs the rate at which the accelerating contacts close, consists of a pendulum arrangement with an escapement similar to that used in a clock (see fig. 35b). This mechanism is connected to the accelerating fingers through a ratchet and pawl. When the start button is pressed (fig. 35c), the solenoid closes the line contact and also tries to close the accelerating fingers, which are prevented from closing by the timing mechanism. However, the escapement permits the gears to rotate at a rate which may be regulated by the adjusting nuts (fig. 35b). When a nut is screwed out, the escapement compels the gears to rotate more slowly, thus increasing the accelerating period. Hence the pawl is permitted to move slowly, allowing the accelerating contacts to close in sequence, each after a definite time interval. The last contact, on closing, connects the motor directly across the line.

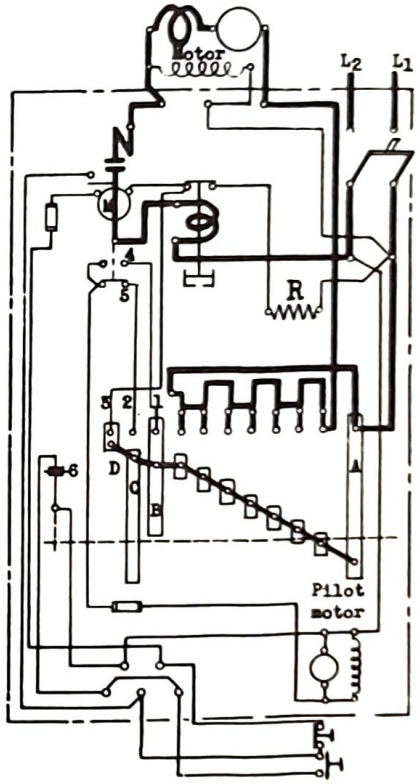
Overload protection is provided by means of a hand-reset temperature overload relay (this type of relay was shown in fig. 15). The bimetal bends when the current through the heater, which is in series with the armature, exceeds a given value, opening the circuit to the solenoid. This allows the contacts to drop open instantly, interrupting the power to the motor. After the bimetal has cooled, the overload relay may be reset by means of a chord.

TIME ELEMENT STARTER WITH PILOT MOTOR.- A time element starter with a pilot motor for timing is frequently used for starting large motors. Such a starter is shown in fig. 36a. The timing motor rotates a drum, through a train of speed reducing gears, which cuts out the starting resistance in steps. With this method cutting out the starting resistance, it is possible to get a very long timing which is accurate and independent of disturbing conditions. Furthermore, the acceleration is smooth under all load conditions, and can be varied by changing the speed of the timing motor.

The wiring diagram of the starter, with a developed view of the drum, is shown in fig. 36b. The ring A keeps all the segments connected to line L_1. When the magnetic switch M is closed, by pressing the "start" button, power is supplied to the motor, with all the starting resistance in the armature circuit, the shunt field being connected directly across the line. At the same time, a



(a)



(b)

Fig. 36 Definite time starter with pilot motor

circuit is formed from L_1, through ring A, segment B, finger 1, auxiliary contact 4, and the pilot motor, to L_2. Thus power is supplied to the pilot motor, which turns the drum. On rotating, the drum cuts out the starting resistance in steps, and forms a contact between finger 2 and segment C. As soon as all the starting resistance is cut out, segment B runs from beneath finger 1, stopping the pilot motor. The main motor thus remains connected directly across the line.

When the "stop" button is pressed, or when the overload trips the magnetic switch M, auxiliary finger 5 on the magnetic switch M completes the pilot motor circuit through finger 2 and segment C, causing the timing motor to rotate the drum back to the starting position. At this point segment C runs from beneath finger 2 and the pilot motor again stops.

Segment D and finger 3 make contact only when the drum is in the "off" position. The drum therefore starts to rotate as soon as switch M is closed, opening the contact between finger 3 and segment D, and inserting R in series with the closing coil. This reduces the holding power.

Contacts 6, which are operated by a cam on the drum, and are held closed when the drum is in the "off" position, are in series with the closing coil. This feature makes it impossible to start the motor unless all the starting resistance is in the armature circuit.

INDUCTIVE TIME ELEMENT STARTER.- Fig. 37 shows a controller of the inductive time limit type. The accelerating contactor (see fig. 37a) provides a definite time delay, which is adjustable from approximately one-half a second to four seconds. A heavy copper tubing is on the magnetic core of the contactor, as well as two coils which are known as a neutralizing coil and a main coil. The neutralizing coil N (figs. 37b and 37c) is connected in series with the coil of the magnetic switch, and the main coil M is connected across the contacts of the magnetic switch.

When the knife switch is closed, a current flows from L_1 (fig. 37c), through coil M, the armature, the starting resistance, and the series field, to L_2. The magnetizing action of the current through coil M holds the accelerating contactor open against an adjustable spring pressure.

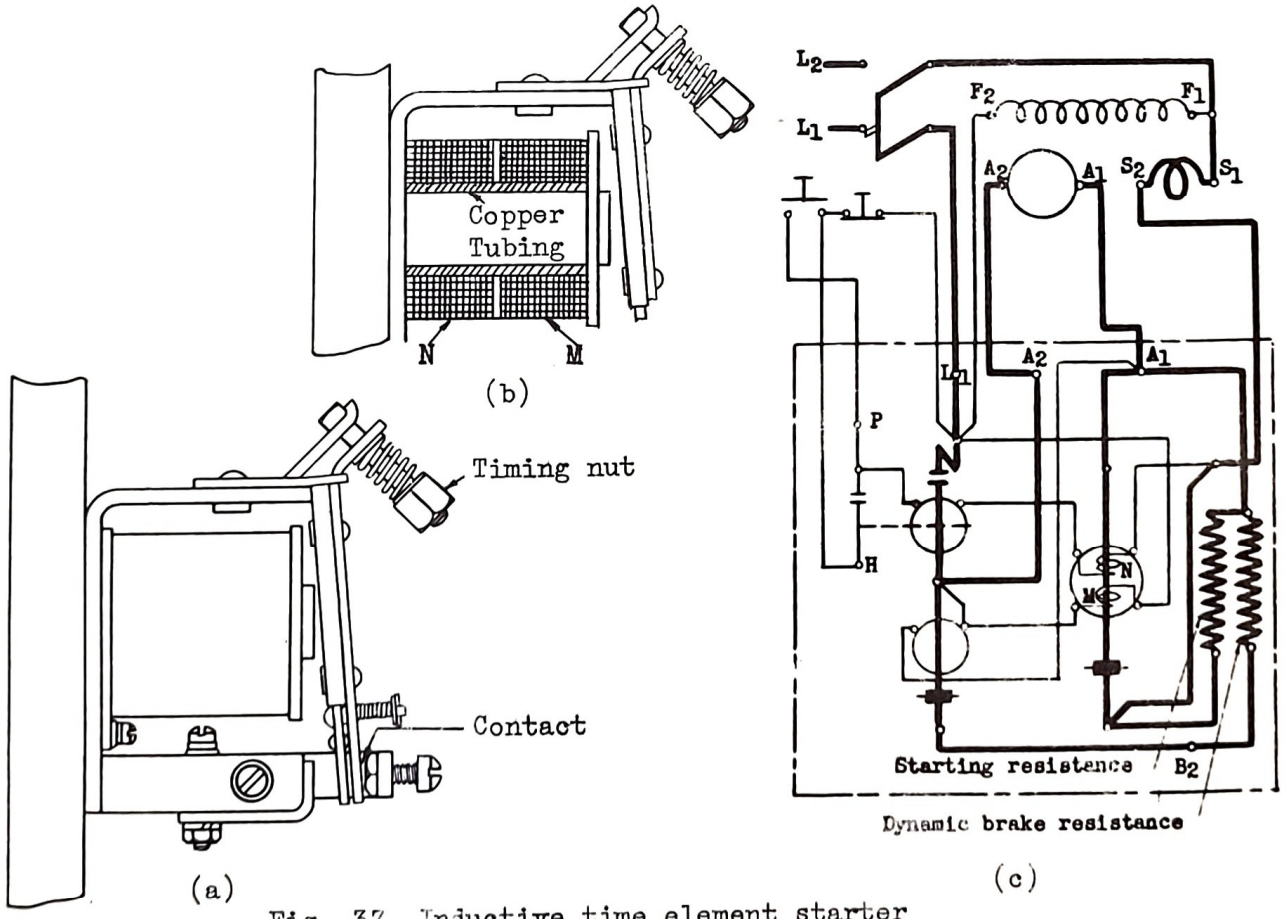


Fig. 37 Inductive time element starter

When the magnetic switch is closed, by pressing the "start" button, coil M is short-circuited and its current reduces to zero. Because the magnetic path of the contactor is a closed circuit of hard steel, the flux set up by coil M would not decrease very much if it were not for coil N. This coil produces a magnetizing action in a direction that will reduce the residual magnetism to zero.

The current in coil N (and therefore the neutralizing action) increases gradually, because of the copper sleeve surrounding the core. This sleeve also prevents the flux from decreasing rapidly. Thus the flux reduces from maximum to zero at a comparatively slow rate. It follows, then, that contactor 1 will close as soon as the residual magnetism decreases sufficiently, connecting the motor across the line. The time delay of the contactor can be varied by changing the spring pressure with an adjustable nut.

LIMIT SWITCHES.- An operator switch is frequently used in connection with equipment in which a definite travel should occur. In such a case an operator cannot be expected to stop the driven equipment just within the safe limits. In fact, in most cases it is desirable to stop the motor automatically just before the driven equipment exceeds the limit of travel. This is accomplished by using a limit switch; one type, manufactured by Mackworth G Rees, Inc., being shown in fig. 31-1.

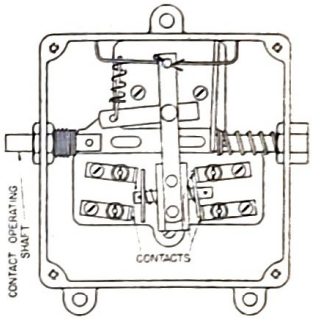


Fig. 31-1
Limit switch

Fig. 31-2 shows a control system using a General Electric controller (fig. 35), an operator switch (fig. 31), and two limit switches placed at the limits of travel. The terminal of coil C, which normally connects to the heater of the overload, is transferred to the + line, and the other terminal is connected to the limit switches. When the handle is in the "reverse" position (see fig. 31b), the circuit of coil C is completed to the negative through limit switch 1. With this position of the operator switch, a short-circuit exists between F and H, having opposite polarity. This is remedied by removing the segment that makes contact with finger F in this position of the switch. Coil C, on becoming energized, closes the accelerating contacts, causing the motor to run in the "reverse" direction. The motor runs until the driven equipment reaches its limit and trips switch 1. This opens the circuit of coil C, which allows the main contacts to open, and stops the motor.

When the handle is shifted to the "forward" position, the circuit of coil C is completed to - through limit switch 2, although F and H are again shorted. This is remedied by removing the segment in contact with finger H. On again becoming energized, coil C closes the main contacts, causing the motor to run in the forward direction. The motor runs until the driven equipment trips switch 2.

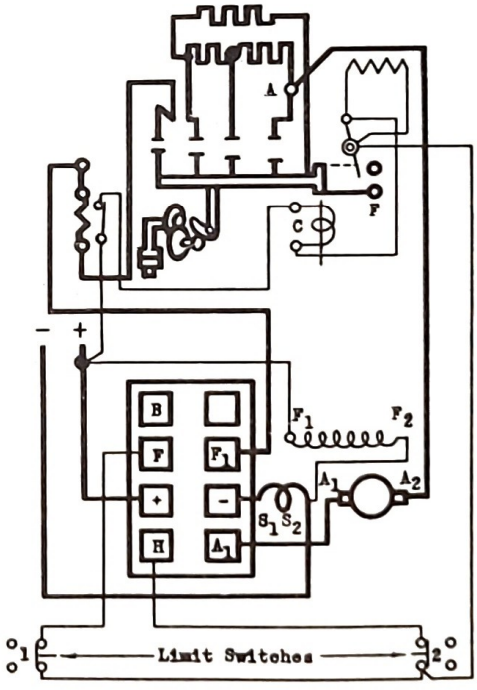


Fig. 31-2
Control system with limit switches

HOME WORK

1. For what industrial applications should time element controllers be used?

2. Make a wiring diagram of a control system that contains a Ford dash pot type starter, an operator switch (see fig. 31), two limit switches, and a compound motor.

Sometimes a combination of the above methods of acceleration is used in one controller. For instance, a popular type of hoisting controller employs relays whose time of closing is a function of time and current, and for this reason they are generally called time-current accelerating relays. These relays are very simple in structure (see fig. 38). They have only one moving part, an aluminum sleeve S, which carries a contact bar B that rests on stationary contacts C when it is in its lowest position. The relay coil is connected in the armature circuit, and the bar B (when making contact) completes the circuit of a contactor coil. The relay functions as follows: The current rises as soon as the circuit containing the relay coil is completed, causing a flux to build up rapidly in the relay. As this flux builds up it passes through sleeve S and induces a voltage in it, setting up a high current. This current establishes a magnetic field in the opposite direction to that established by the coil. These two opposing fields cause the sleeve to move upward. The repelling force would cause the sleeve to move with considerable speed if it were not for the fact that the sleeve passes through the magnetic field as it starts to move upward, setting up a second current in the sleeve. This second current (called eddy current) causes a retarding action, and combines with the force of gravity to allow the sleeve to move slowly upward for a short distance. The sleeve starts to fall after reaching its highest point, and in so doing it again cuts flux, setting up eddy currents which retard the downward motion. This retarded motion of the sleeve provides the time of acceleration, which for maximum current is as high as 2.75 seconds.

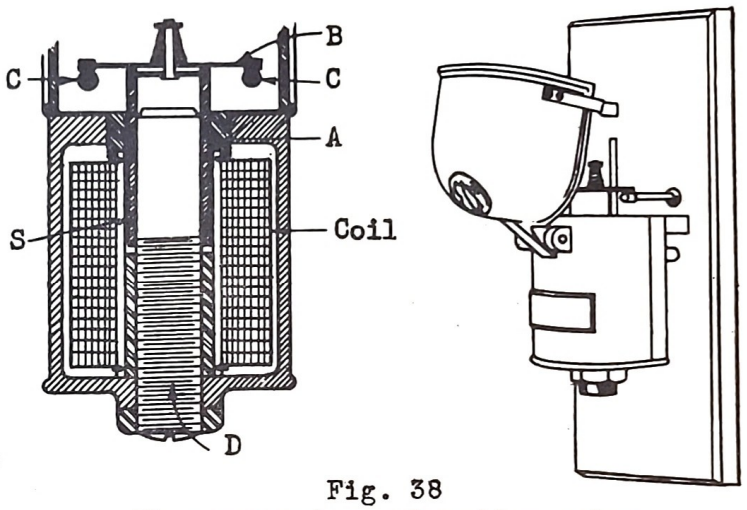


Fig. 38
Time-current accelerating relay

Since the relay coil current governs the flux strength, it is apparent that a lower current will cause the sleeve to move upward a shorter distance, so that contacts C will be open for a shorter period. The contacts of such a relay are capable of carrying only a small current. Therefore they are not suitable for carrying the current of the main circuits of a controller, but may be used to complete the circuit of a contactor coil.

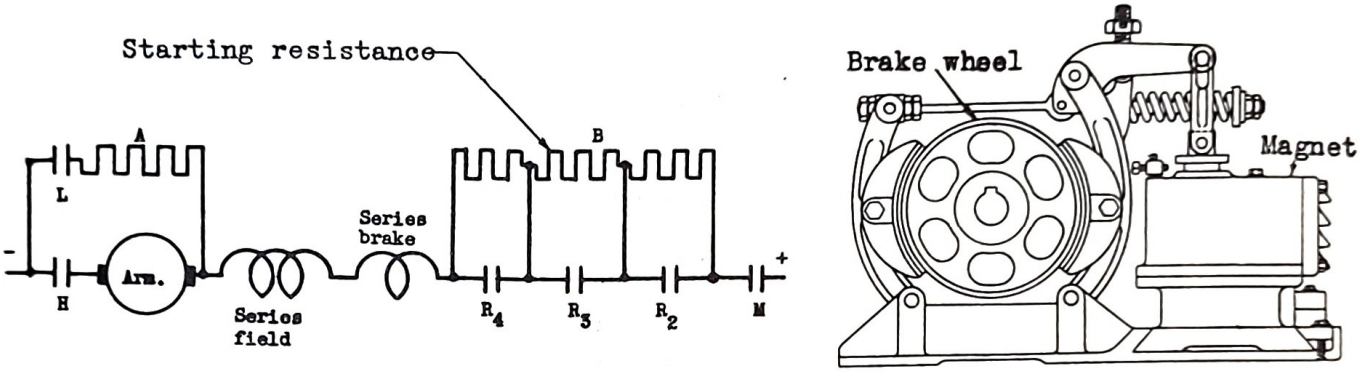
The time of acceleration of the relay may be varied by regulating the threaded core D. When the core is screwed out, the air gap A increases, reducing the flux. Less current is then set up in the aluminum sleeve. The sleeve then rises a shorter distance, thus reducing the accelerating time.

HOISTING.- The connections in a hoisting controller during the hoisting period are usually as shown in fig. 39a. The series brake (one type of which is shown in fig. 39b) is mounted on one end of the armature shaft and locks the motor when no current flows through its coil. This brake holds the load when the motor is disconnected from the power line. The contactors L, H, R_2, R_3, R_4, and M are all operated in proper sequence by means of a master switch. Contactors L, H, and M close when the handle of the master switch is moved to the first hoisting position. The main circuit is from -, through contactor H, armature, field, brake, starting resistance B and contactor M, to +. Some current is also shunted around the armature, through resistance A. The armature receives little current with these connections, giving a very low speed.

Moving the handle to the second hoisting position opens contactor L and removes the shunting resistance A. This increases the armature current, and therefore increases the motor speed.

Moving the handle to the successive hoisting positions closes contactors R_2, R_3, and R_4 in consecutive order, connecting the motor across the line.

The motor is thus operated as a series machine during hoisting. Five hoisting speeds are secured, varying from a very low speed for the first position of the handle to the highest speed when the motor is connected directly across the line.



(a) (b)

Fig. 39
Motor and controller connections during the hoisting period

LOWERING.- When a crane load is being lowered, it will overhaul the load if it is heavy enough to overcome friction. Usually a load of about one-third the rated capacity of the crane is enough to overcome the friction of the hoisting machinery. Any load exceeding this would cause a motor to be overhauled if means were not provided to prevent this. Overhauling is prevented by connecting the motor as a shunt machine (a shunt machine runs at an approximately constant speed at all loads, as discussed in Lesson 37). If a load tends to overhaul a shunt-connected motor, the machine prevents this by automatically becoming a generator, supplying a counter-torque, and returning power to the supply lines. When the load is not heavy enough to overcome friction, the motor furnishes the necessary extra power to lower the load.

A wide lowering speed range is secured by changing the field strength, just as the speed is changed in any shunt motor.

The connections during the lowering period are shown in fig. 40. Contactors L, S, R_2, R_3, R_4, and M close when the handle is moved to the first lowering position. This connects the motor as a shunt machine, with the friction brake in the field circuit. The circuit is from -, through contactor L, through resistance A, after which it divides into two circuits. One of these is through the field, brake, contactors R_4, R_3, and R_2 (which completely short-circuits resistance B), through contactor M, to +. The other circuit is through the armature, resistance C, contactors S and M, to +. The current through the first circuit sets up a flux in the field and causes the friction brake to release. The current through the second circuit flows through the armature in the proper direction to lower the load. These connections provide the greatest field strength and the lowest armature current. Thus the motor runs at the lowest speed.

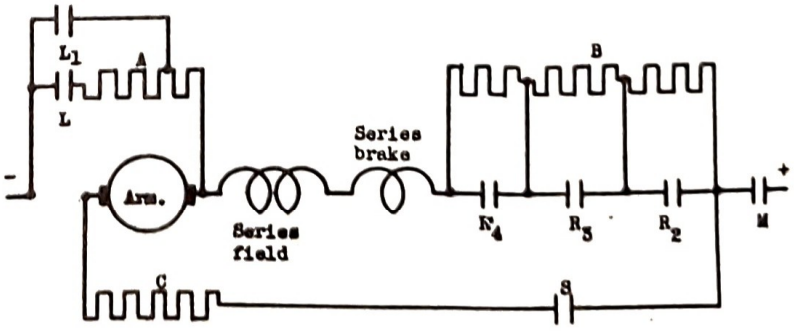


Fig. 40 Connections of motor and controller during lowering period

Moving the handle to the two next lowering positions opens contacts R_4 and R_3, inserting two steps of resistance in the field circuit. This weakens the field and causes the motor speed to increase.

Moving the handle to the fourth lowering position closes contactor L_1. This shorts out a section of resistance A, causing an increase in armature current and motor speed.

Moving the handle to the last position opens contactor R_2, placing the last step of resistance in the field circuit. This provides the highest lowering speed.

STOPPING.- Fig. 41 shows the connections when the handle is in the "off" position. In this case only contactor E is closed. This connects the armature, series field, and resistance E in a closed circuit. If for some reason the load should overhaul, the motor would function as a series generator, forcing current through resistance E. This would cause the machine to develop a counter-torque, allowing the load to descend at a low speed. Thus a safety feature is provided, which is effective if the friction brake fails to hold the load.

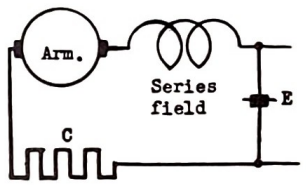


Fig. 41
Connections of motor and controller during dynamic brake period

The structure of a controller, which functions as explained above, is shown in fig. 42. Its wiring diagram is shown in fig. 43. (In these figures the resistors and contactors have the same designations as those of the preceding figures.)

In fig. 43 it will be noted that accelerating relays are provided, which are connected in the armature circuit. These are of the time-current type, and each closes a circuit to a coil of an accelerating contactor as soon as the current falls to a value for which the relays are set to operate. In other words, these relays provide time-current limit acceleration during hoisting.

Note further that all contactors except E are designed to close when their coils are energized. Contactor E is designed to be held closed by a spring, and opens only when its coil is energized.

In fig. 43, the following circuits are made when the handle of the master switch is moved to the first hoisting position:

A circuit is made from -, through the master switch to terminal M, through the coil of contactor M, to +. Contactor M thus closes, inserting resistance r in series with the closing coil and preventing the coil from over-heating and reducing the holding power.

A second circuit is formed from -, through the master switch to terminal H, through the coil of contactor E, to +. The coil of contactor H is also connected to the same control circuit wire, but is short-circuited by the auxiliary contacts of contactor E. Then contactor E must open before the coil of contactor H can become energized, thus closing this contactor.

A third circuit is formed from -, through the master switch to terminal L, through the auxiliary contacts of the closed contactor H to the bottom of contactor S, and then through contactor M to +. Contactor L thus closes.

Contactors M, H, and L are now closed, and E is open (see fig. 39a).

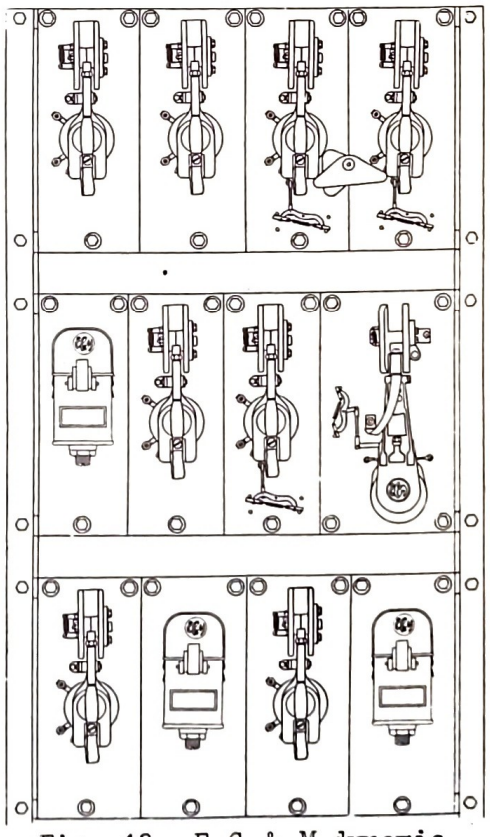


Fig. 42 E C & M dynamic brake hoisting controller

It was explained that H could not close until E had opened, and L could not close until H had closed. Without such an interlocking system the controller would not be reliable. For instance, suppose that L and M in fig. 39a are closed, and H is open. Current would then flow through the magnetic brake and release it, but no current would flow through the armature. This would allow the load to overhaul the motor.

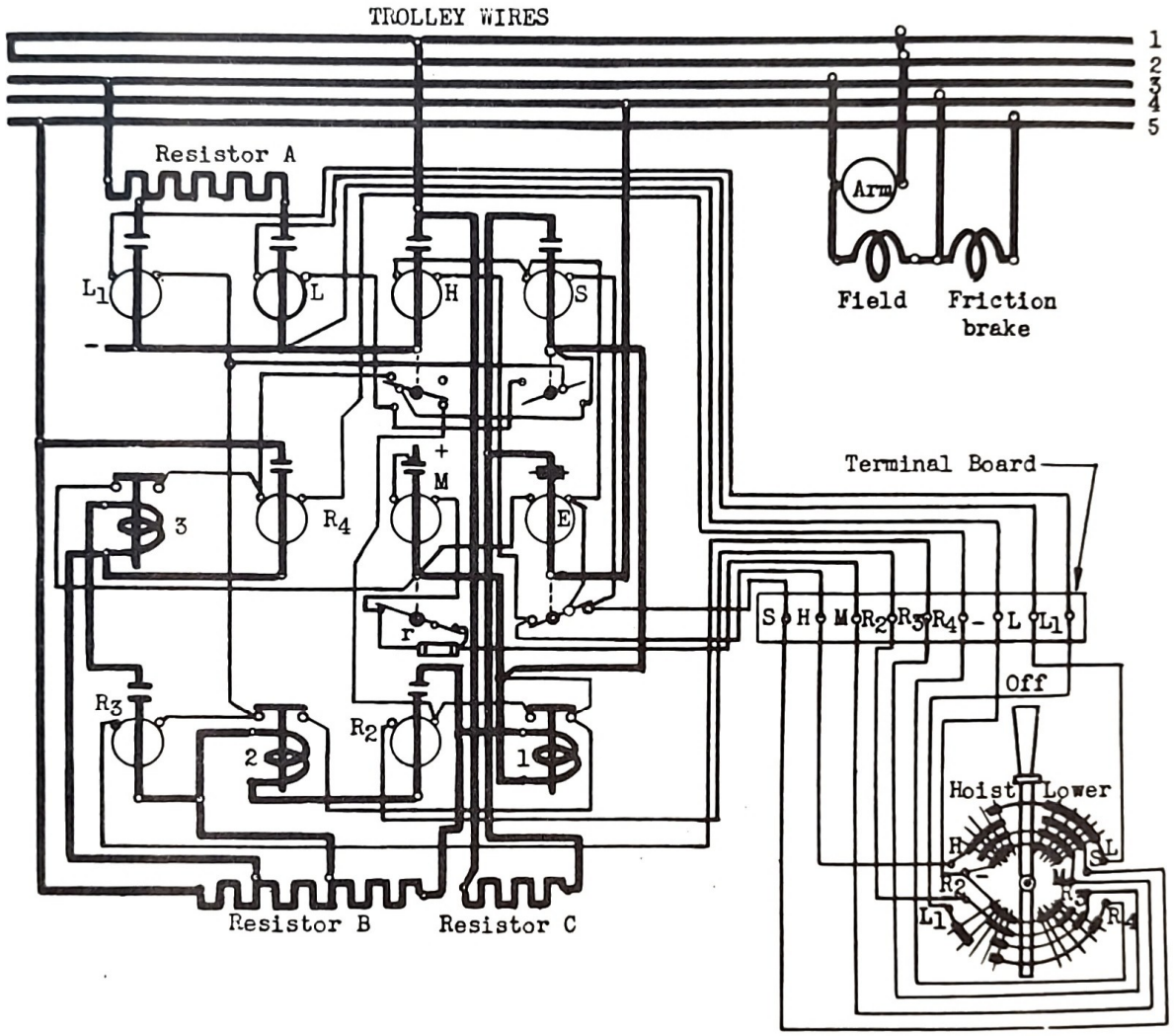


Fig. 43 E C & M dynamic brake hoisting controller

The lowest hoisting speed is provided with contactors M, H, and L closed and E open (see fig. 39a).

When the handle is moved to the second hoisting position, all the circuits remain the same, except the one including the coil of contactor L. This circuit is opened, removing the armature shunting resistance A and thereby increasing the speed of the motor.

Moving the handle to the third position adds a circuit, which is from - on the master switch to terminal R_2, through the coil of contactor R_2 to a contact of the time-current relay 1. As soon as the current through this relay drops to a value for which it is set, the coil circuit of contactor R_2 is completed. This causes R_2 to close, short-circuiting a section of the starting resistance and again increasing the motor speed. After R_2 closes, relay 2 is inserted in series with the armature.

Moving the handle to the fourth position closes contactor R_3 as soon as the current drops to the value for which relay 2 is set. This shorts out a second step of resistance and inserts relay 3 in the armature circuit.

Moving the handle to the last position closes contactor R_4 as soon as relay 3 operates. This connects the motor directly across the line, giving the highest speed.

LOWERING.- The following circuits are made when the handle is moved to the first lowering position:

A circuit is made from - on the master switch to terminal M, through the coil of contactor M, to +. Contactor M closes, inserting r in the control circuit.

A second circuit is from -, through the master switch to terminal R_4, through the coil of contactor R_4 and one auxiliary contact of H to the bottom of contactor S, through contactor M, to +. Thus R_4 closes. Note that this circuit can be formed only when contactor H is open.

A third circuit is from -, through the master switch to terminal R_2, through the coil of contactor R_2 and one auxiliary contact of H to the bottom of contactor S, through contactor M, to +. Thus R_2 closes. As in the case of R_4, contactor R_2 can close only while contactor H is open.

A fourth circuit is from -, through the master switch to terminal S, through an auxiliary contact and coil of contactor E, through contactor M, to +. Contactor E opens, inserting the coil of contactor S in series with that of E, causing contactor S to close. Thus contactor S cannot close until E opens.

A fifth circuit is from -, through the master switch to terminal L, through the coil of contactor L, through closed auxiliary contacts of S, through the bottom of contactor S, through contactor M, to +. This circuit, which cannot be established until contactor S is closed, closes contactor L.

A sixth circuit is from -, through the master switch to terminal R_3, through the coil of contactor R_3, through one closed auxiliary contact and to the bottom of contactor S, through contactor M, to +. This circuit, which also cannot be established until contactor S is closed, closes contactor R_3.

Contactor E is now open and contactors L, S, R_2, R_3, R_4 and M are closed (see fig. 40). This provides the lowest speed for lowering.

When the handle is moved to the second lowering position, the coil circuit of contactor R_4 is opened. Contactor R_4 on opening inserts a section of resistance B in series with the field, increasing the speed of the motor.

Moving the handle to the third position opens the coil circuit of contactor R_3. R_3 on opening inserts another section of resistance B in the field circuit, providing a weaker field and a higher speed.

When the handle is moved to the fourth position, a circuit is made from -, through the master switch to terminal L_1, through the coil of contactor L_1, through one contact of S to the bottom of contactor S, through contactor M, to +. Contactor L_1 closes, shorting out part of resistance A, causing more current to flow in the armature and thereby giving a higher speed.

Moving the handle to the last lowering position opens the coil circuit of contactor R_2. R_2 on closing inserts the remaining portion of resistance B in the field circuit, providing the weakest field strength and giving the fastest lowering speed.

OFF.- When the handle is in the "off" position, the - terminal is disconnected (in the master switch) from all the contactor coils. Then all the contactors except E will be open. Contactor E establishes the connections shown in fig. 41, providing the dynamic brake action explained in connection with this figure.

NEED FOR A DUPLICATE TROLLEY WIRE.- In fig. 43 note that one terminal of the armature is connected to trolley wires 1 and 2 by two separate collectors. If only one collector and trolley wire were used, the collector might slip off the trolley wire when a load was being lowered. Current would then flow through the series field and friction brake, but none would flow through the armature. The friction brake would then release and a heavy load would descend rapidly, for the motor would supply no counter-torque. With the use of two trolley wires, however, one collector will maintain the circuit even though the other should slip off.